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T-55 Engine Compressor Stator Vane Investigation

by Scott M. Grendahl

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Weapons and Materials Research Directorate, ARL

Abstract

The U.S. Army Aviation and Missile Command (AMCOM) requested the U.S. Army Research Laboratory-Weapons and Materials Research Directorate (ARL-WMRD) investigate a corrosion problem with T-55 engine stators. This investigation was part of a second source vendor qualification in which a specific vendor was failing the engine test due to significant corrosion. The stators were virtually identical before the engine test and seemingly had passed all qualification standards. The original equipment manufacturer (OEM) of the T-55 engine stator was Avco Corporation - Lycoming Division, Stratford, CT. The second source vendor being qualified was Electro-Methods Incorporated (EMI), South Windsor, CT, and EMI's coating subcontractor, Microfin Corporation, Providence, RI. ARL-WMRD performed a detailed investigation that stipulated several recommendations. Some of these recommendations were adopted, and further testing was performed. The final testing of the T-55 stators that incorporated the ARL-WMRD recommended changes provided data that indicated the engine test would be successful. Upon subsequent engine testing, acceptable results were achieved with the new corrosion-resistant coating system.

Acknowledgments

The author would like to thank Mr. Randy McFarland of Westar Corporation, Huntsville, AL for his input and enlightening discussions of this work. The author would also like to acknowledge Mr. Joshua Nisenbaum and Mr. Christopher Singer, both of the U.S. Army Research Laboratory-Weapons and Materials Research Directorate (ARL-WMRD), for their data contributions.

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1. Introduction

The objective of this effort was to resolve a corrosion failure of second source vendor components into tangible parameters that could be modified. A subsequent goal was to attain a modified design that would meet the corrosion requirement of the engine performance test.

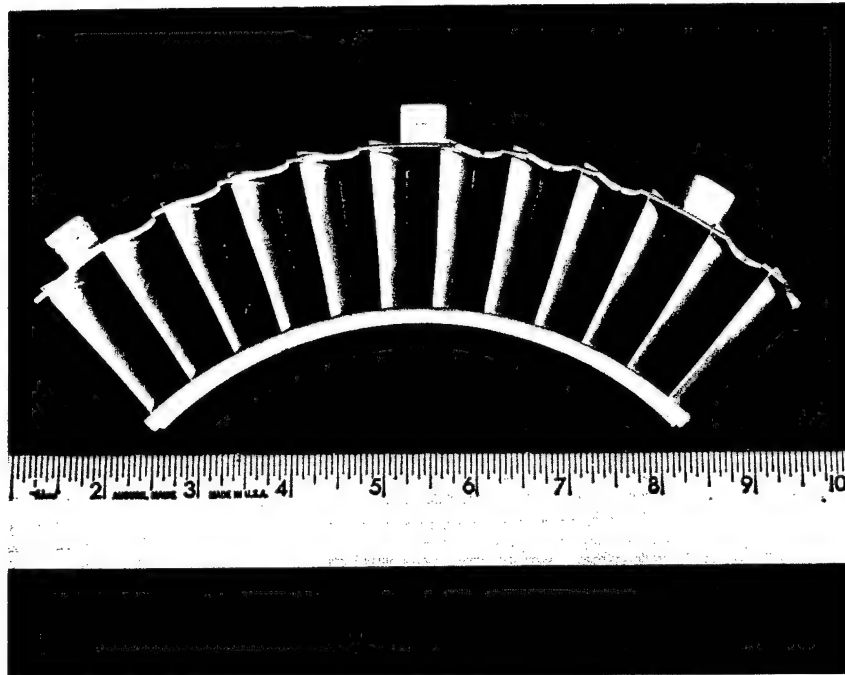
2. Experimental Procedure

This investigation was conducted in three segments. The first characterized the initial probable causes of the failed engine corrosion test, the second investigated a modified design of the corrosion-resistant coating system, and the third involved examining the properties of the corrosion-resistant coating developed from the U.S. Army Research Laboratory-Weapons and Materials Research Directorate (ARL-WMRD) recommendations. ARL-WMRD conducted examinations of the components that included the following:

- a. Visual Examination/Light Optical Microscopy.
- b. Adhesion Testing – Mandrel Bend Testing.
- c. Corrosion Resistance Testing – Salt Fog Resistance.
- d. Coating Thickness Measurement.

3. Phase One – Initial Characterization

3.1 Sectioning. The sixth stage engine compressor stator vane assembly is governed by Avco Corporation's Drawing Package 2-100-060-26 [1]. Figures 1 and 2 depict the stator vane assembly initially sectioned in half. Figure 2 shows the additional dissection of the component for examination and testing. Portions of the individual vanes were needed for bend and



Mates With
Figure 2.

Figure 1. Sectioned Half of the Stator Vane Assembly (Reduced Approximately 0.75×).

ARL Salt Fog
Portion

Bend Test
Vane

Sent to Electro
Methods Inc.

ARL Cross-
Section Mounts
and Salt Fog
Vane Specimen

Mates With
Figure 1.

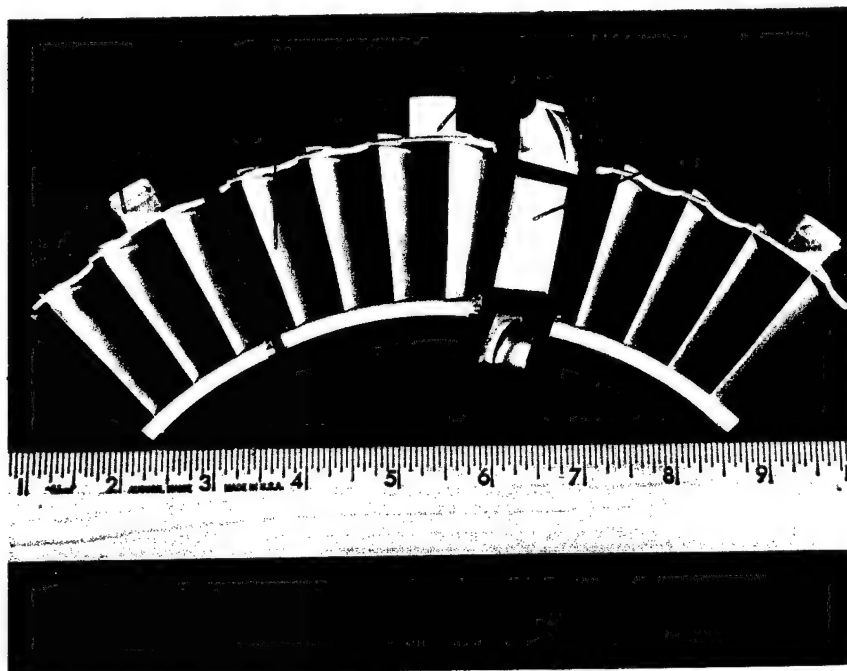


Figure 2. Additional Dissection of the Stator Vane (Reduced Approximately 0.75×).

corrosion testing as well as for the coating thickness measurements. Two three-vane segments of the component were also sectioned, one of which was sent to Electro-Methods Inc. and one subjected to corrosion testing at ARL-WMRD.

3.2 Visual Examination/Light Optical Microscopy. The visual examination requirement for the coating system of these components was addressed in AMS 2400 Revision (Rev.) S, entitled "Cadmium Plating" [2]. Specifically, in section 3.5, "Plated cadmium shall be smooth, continuous, adherent to the basis metal, uniform in appearance, and essentially free from pin holes, porosity, blisters, nodules, pits and other imperfections detrimental to usage of the plating." The stator vane assembly, when viewed in visible light, was dull silver/gray in color, indicative of pure cadmium. The as-received condition of the stator assembly, included small black spots that were more prevalent where the individual vanes were brazed to the inner (brass) shroud. However, the individual vanes also contained black spots, which appeared to be the result of corrosion, as shown in Figures 3 and 4. The figures depict both the concave and convex sides of an individual vane that contained corrosion. The arrows in the figures highlight several examples of the black corrosion spots.

Figure 5 depicts a typical "black spot" at higher magnification. White product can be seen inside this particular "black spot," which is more clearly defined as a corrosion pit. The areas where the vanes were brazed to the inner shroud contained what appeared to be corrosion stains. It is within these stains where pitting was predominant, as shown in Figure 6. The characteristic bronze or iridescent yellow hue of a chromic acid sealer was not observed. However, it should be noted that a thinner coating would result in a clear chromic acid coating.

The previous findings obviously constituted failure of the visual requirements stipulated by AMS 2400 Rev. S [2]. The corrosion observed on the as-received components was indicative of a coating system that was not capable of providing protection under normal environmental conditions. It was readily apparent that this coating system would not be adequate to pass the engine corrosion test requirement, an environment much more severe than our standard atmosphere.

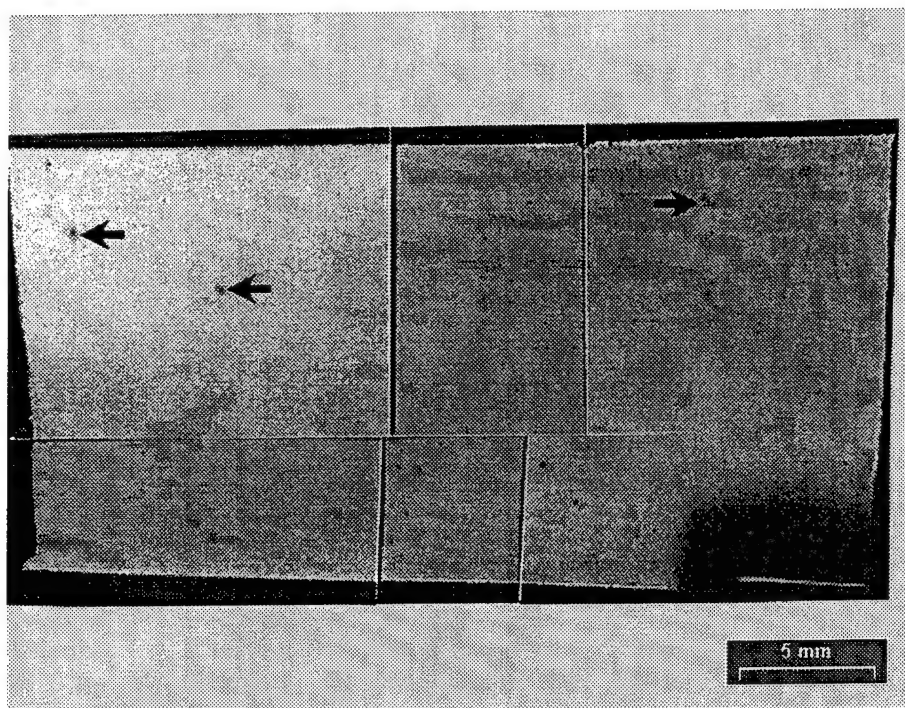


Figure 3. Concave Side of a Single Vane Showing Corrosion Pits.

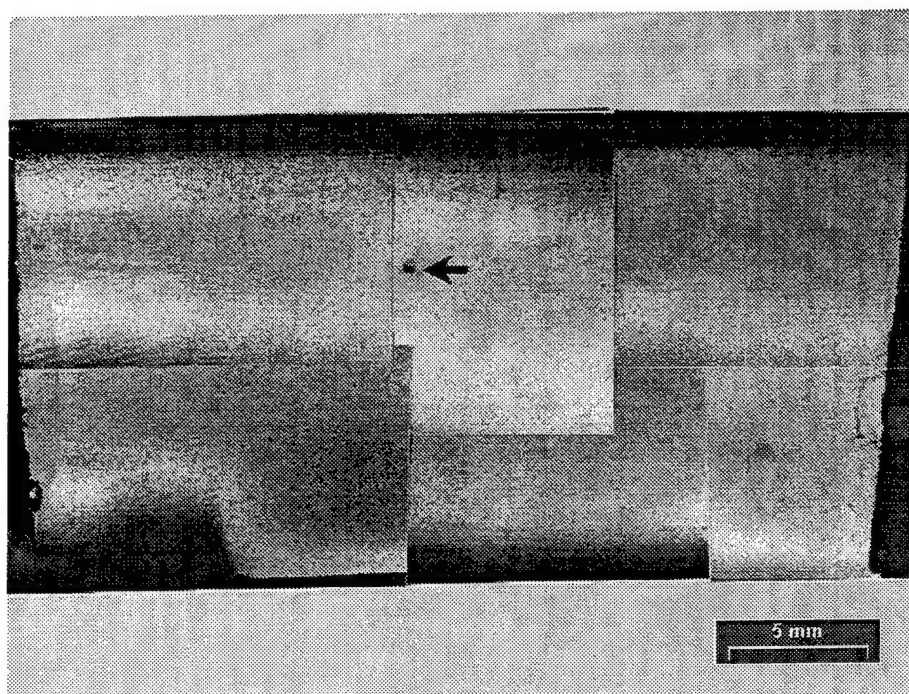


Figure 4. Convex Side of a Single Vane Showing Corrosion Pits.

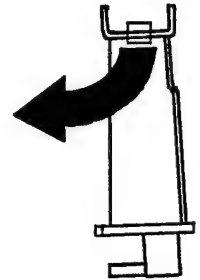
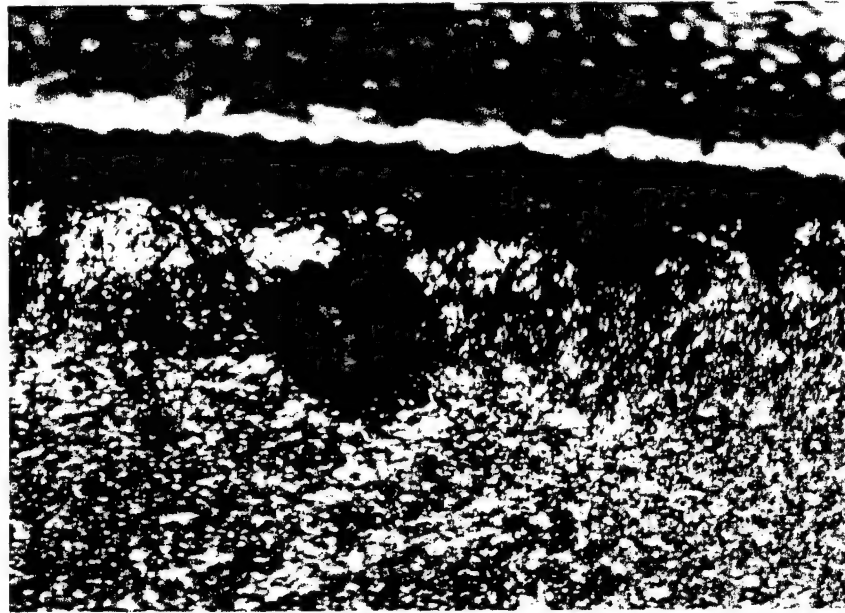


Figure 5. Typical Corrosion Pit Found on the Stator Vane Assembly (Magnified 65×).

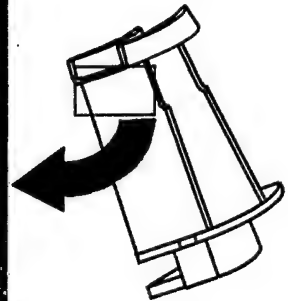
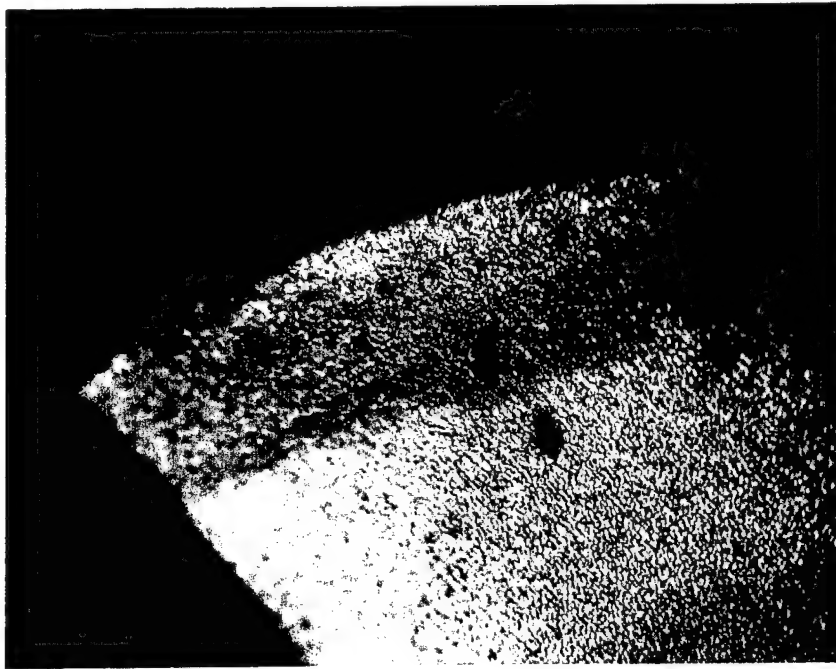


Figure 6. Black Corrosion Pits Near Braze of Vane to Brass Shroud (Magnified 10×).

3.3 Bend Testing. The adhesion requirement of the coating system on these components is also governed by AMS 2400 Rev. S [2]. Section 3.4.2 of AMS 2400 Rev. S states that

specimens shall not show separation of the plating from the basis metal, when examined at 4× magnification, after being bent rapidly, in accordance with ASTM-E-290, through an angle of 180° around a mandrel with a diameter equal to the thickness of the specimen [2, 3]. A single vane was carefully sectioned from the interior and exterior shroud of the assembly. The sectioned vane was then bent around a mandrel with a diameter approximately equal to the thickness of the vane. The bent vane can be observed in Figure 7. No evidence of failure was noted.

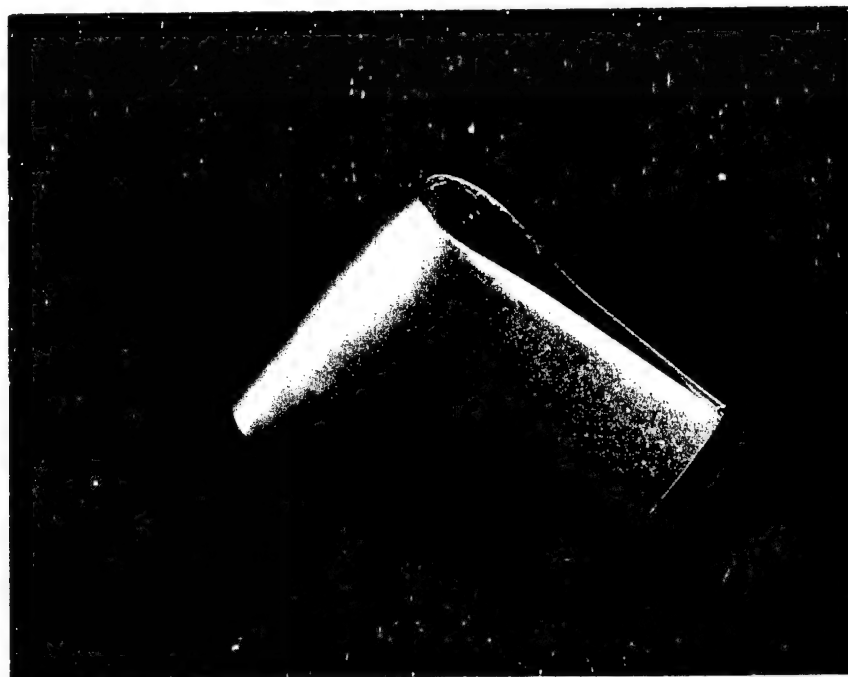


Figure 7. ARL Vane Bend Test Specimen (Magnified Approximately 3×).

3.4 Corrosion Testing. According to AMS 2400 Rev. S, ferrous metal parts shall show no visual evidence of corrosion of the basis metal after being subjected to a 200-hr continuous salt fog exposure conducted in accordance with ASTM-B-117 [2, 4]. The assembly in the as-received condition would have failed the corrosion resistance test criteria based upon the visual examination, due to the presence of the dark corrosion pits. However, the test was conducted to alleviate doubt. Figures 8, 9, and 10 show the vanes after 24, 125, and 200 hr of exposure, respectively. The dark corrosion spots increased in magnitude, and corrosion of the base metal occurred, constituting failure. Figure 10 is a color depiction to more clearly

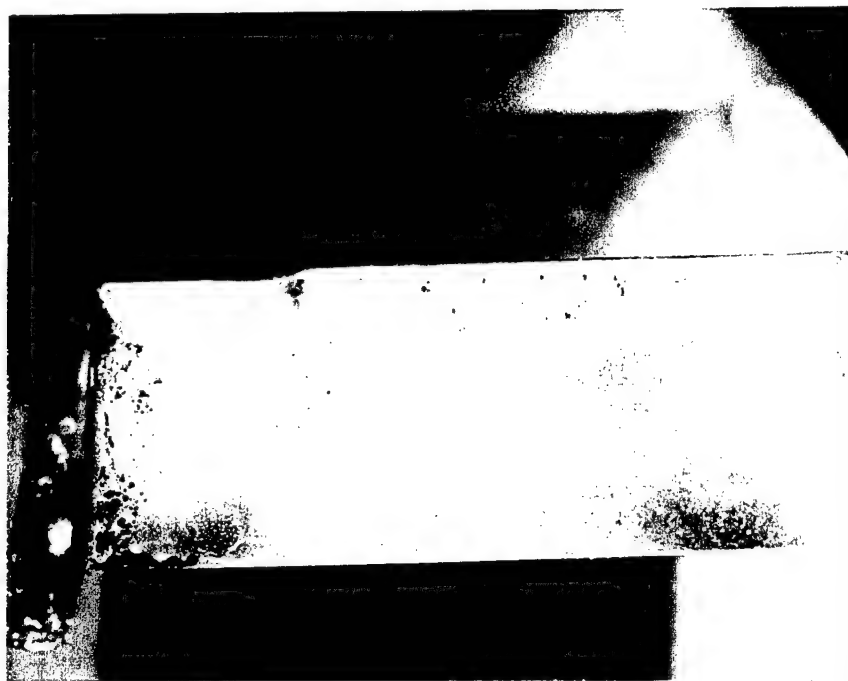


Figure 8. Typical Vane Corrosion After 24 hr Salt Fog Exposure (Magnified Approximately 3 \times).

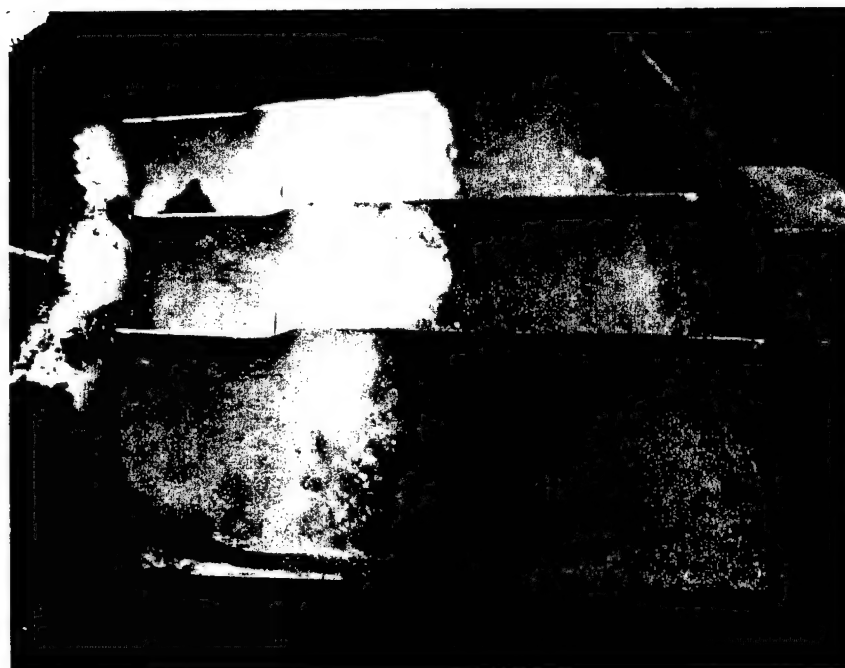


Figure 9. Typical Vane Corrosion After 125 hr Salt Fog Exposure (Magnified Approximately 3 \times).



Figure 10. Typical Vane Corrosion After 200 hr Salt Fog Exposure (Magnified Approximately 3 \times).

demonstrate the magnitude of the corrosion. The stator section obviously failed the corrosion resistance requirement.

3.5 Coating Thickness. These components were designated to have a 2400-3 coating system, according to AMS 2400 Rev. S [2]. Table 1 of AMS 2400 Rev. S lists the thickness requirement for designation 2400-3 as 0.0003–0.0005 in, with the only exception being that this only applies to areas that can be touched by a 0.75-in-diameter sphere, as established in section 3.4.1.4 [2]. Cross-sections of several vanes were prepared metallographically and examined per ASTM-B-487 [5]. Figure 11 shows a representative area along the convex side of a vane near the inner shroud where the cadmium plating was approximately 0.0003 in thick. In contrast, Figure 12 is indicative of the nonuniform cadmium plating observed on much of the concave side of a vane near the inner shroud. In this area there is only a hint of plating evident, which would account for the poor corrosion resistance.

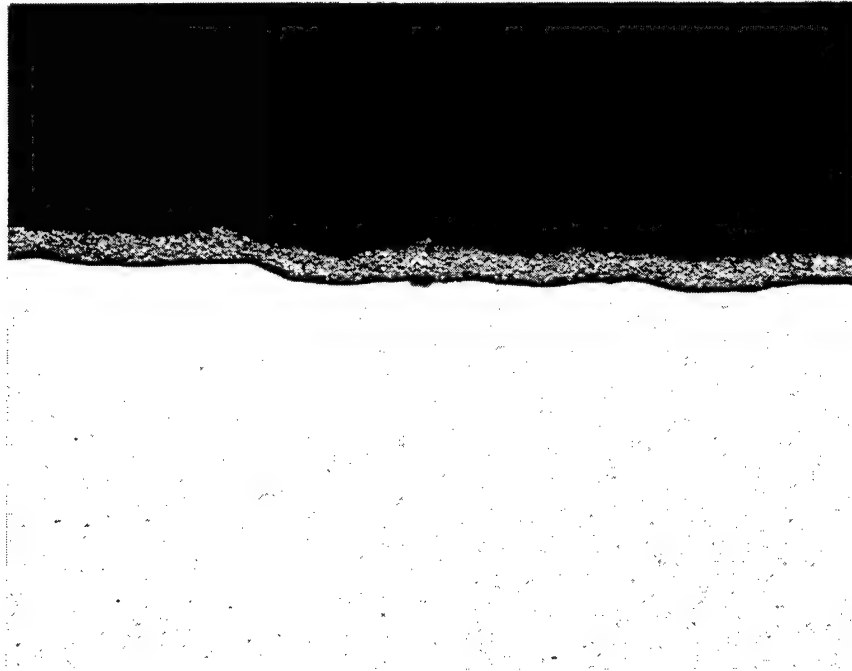


Figure 11. Cadmium Plating Thickness on the Convex Side of the Vane (Magnified 500×).

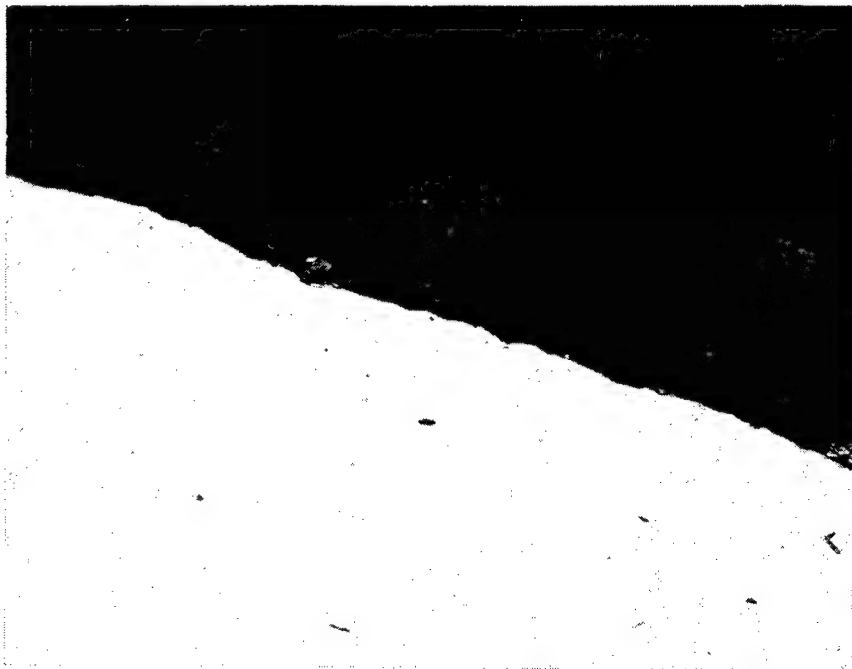


Figure 12. Cadmium Plating Thickness on the Concave Side of the Vane (Magnified 500×).

Realistically, a sphere with a diameter of 0.75 in cannot touch these areas due to the fact that they are near corners. These figures are presented only to represent the variation in coating thickness and to provide a reason why these components performed so poorly under corrosion resistance testing. Conversely, Figures 13 and 14 represent the middle sections of a single stator vane where they could be touched by a 0.75-in-diameter sphere and, therefore, should have a minimum cadmium thickness of 0.0003 in.

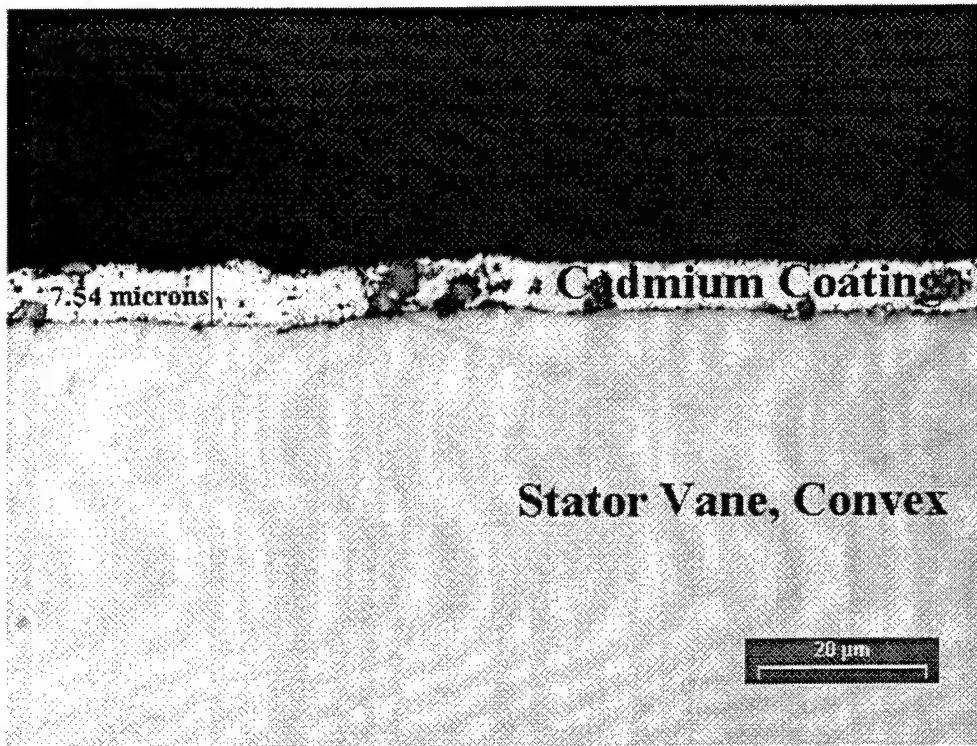


Figure 13. Typical Plating Thickness on the Convex Side of the Vane.

Measurements were taken in several locations along the components. The results show that the coating was thin in most locations but especially near the inner shroud where corrosion was abundant after the 200-hr salt fog test. Table 1 presents the cadmium thickness measurements, including the locations, taken on the part.

3.6 Scanning Electron Microscopy (SEM)/Energy Dispersive Spectroscopy (EDS) Examination. Portions of the sectioned components were examined by SEM. Specifically, the

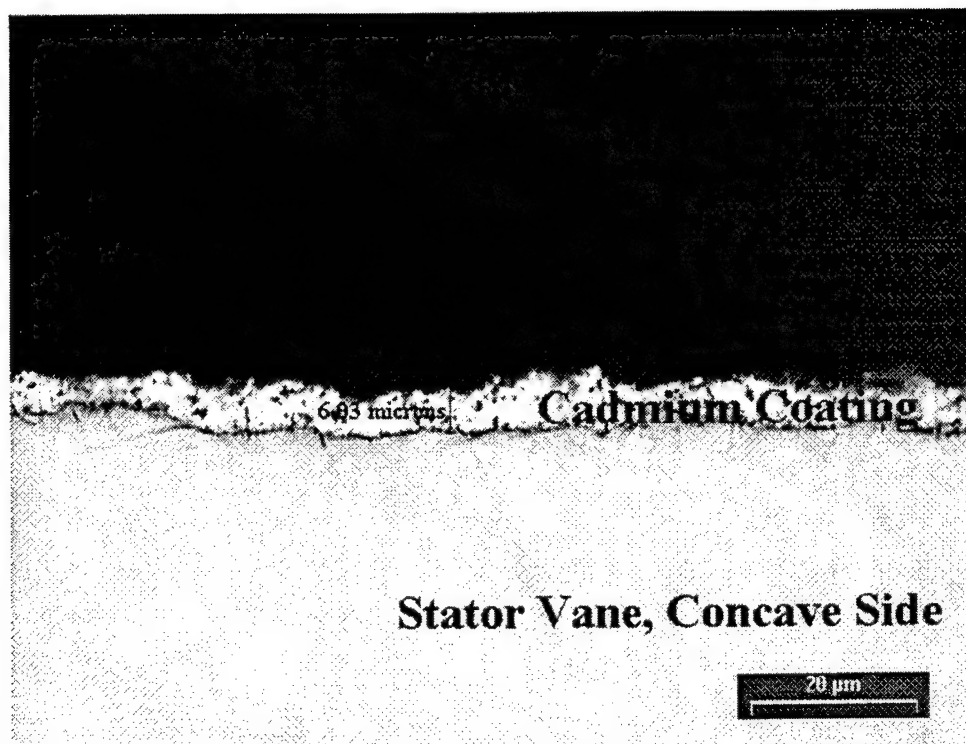


Figure 14. Typical Plating Thickness on the Concave Side of the Vane.

Table 1. Cadmium Thickness Measurements

Component	Location	Measurement (mils)
<u>Shrouds</u>	Outer Shroud	0.27
	Inner Shroud	0.26
<u>Vanes</u>		
• Near Outer Shroud	Concave Side	0.33
	Convex Side	0.39
• Middle of Vane	Concave Side	0.28, 0.21 ^a
	Convex Side	0.29, 0.24 ^a
• Near Inner Shroud	Concave Side	0.0–0.12 ^b
	Convex Side	0.0–0.28 ^b

^a Denotes that measurements were taken from two samples.

^b Denotes a range of thickness due to nonuniformity of coating.

dark areas of corrosion were verified to be pits containing a significant amount of corrosion product. A cadmium plating was detectable on all surfaces; however, in some instances, base metal elements were also detectable, indicating a thin or discontinuous coating. Figures 15 and 16 show the corrosion product within the pits in both secondary and backscatter electron imaging, respectively.

These corrosion pits were found to extend to the base metal as evidenced by the Fe peak in the EDS spectrum. This is depicted in Figure 17.

Specification AMS 2400 Rev. S stipulates that the cadmium must be sealed with a chromic acid sealant or with a chromate or phosphate treatment when specifically approved [2]. An attempt was made to verify the existence of a chromium or phosphorus sealer over the cadmium coating. These sealers would be evidenced by the presence of the elements Cr or P, respectively, within the EDS spectrum. Neither element was observed above the scatter within the EDS spectrum. Figure 18 presents the EDS spectrum from a representative stator vane. The only elements observable in Figure 18 are oxygen (O) and cadmium (Cd). To further investigate, a cadmium-plated nut known to have a chromate sealer was analyzed and indeed was found to contain a significant amount of the element Cr within, or on top of, the cadmium coating. Figure 19 presents the EDS spectrum showing the Cr peak. These findings suggest that either the sealer was absent or below detectable limits. In either case, the corrosion protection afforded would be minimized.

3.7 Preliminary Findings. ARL-WMRD concluded that the failure of the engine corrosion resistance test was due to inadequate cadmium plating and more than likely inadequate sealing of the coating. Suggestions were made to increase the thickness of the cadmium to the specified level and to provide an adequate sealant. It was conceded, however, that the governing specification AMS 2400 Rev. S might not have a sufficient cadmium thickness requirement to pass 200 hr of salt fog resistance for these components [2]. Since this specification contains the clause "when such surfaces of parts can be touched by a sphere 0.75 inches in diameter," the requirement becomes suspect. Such a sphere cannot touch the vast majority of this part. The

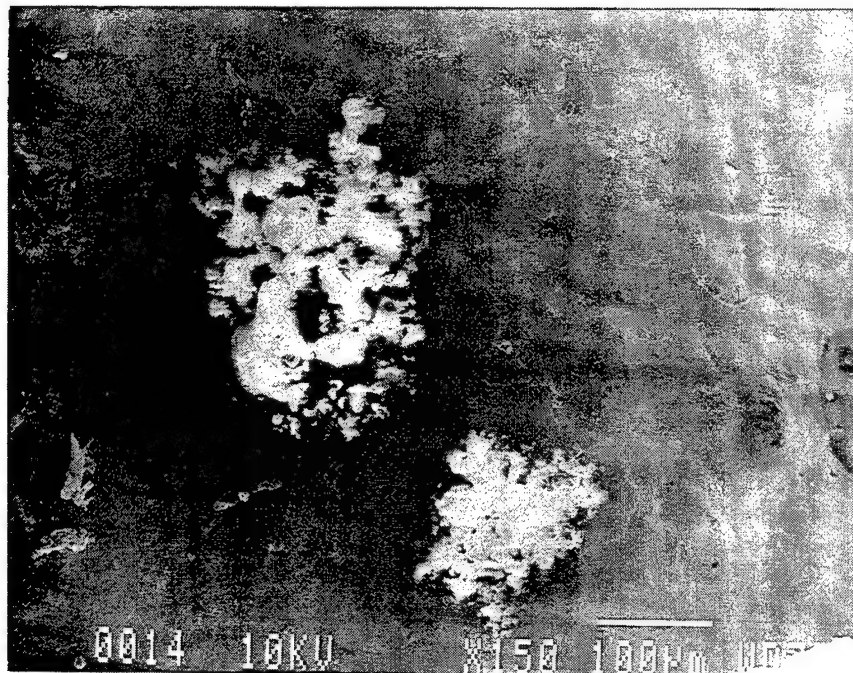


Figure 15. Secondary Electron Image of Corrosion Product Within a Pit (Magnified 150×).

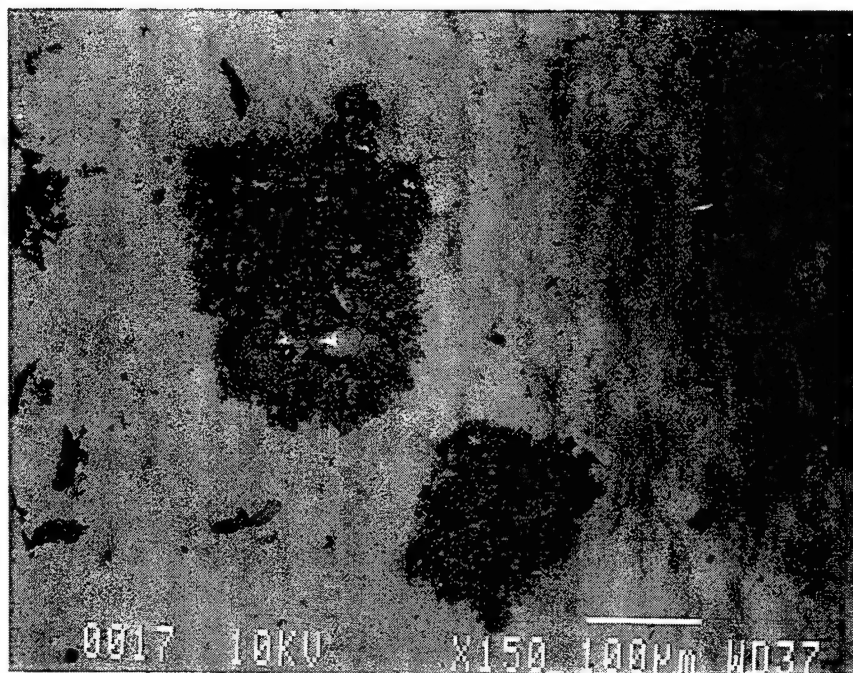


Figure 16. Backscatter Electron Image of the Product Within a Pit (Magnified 150×).

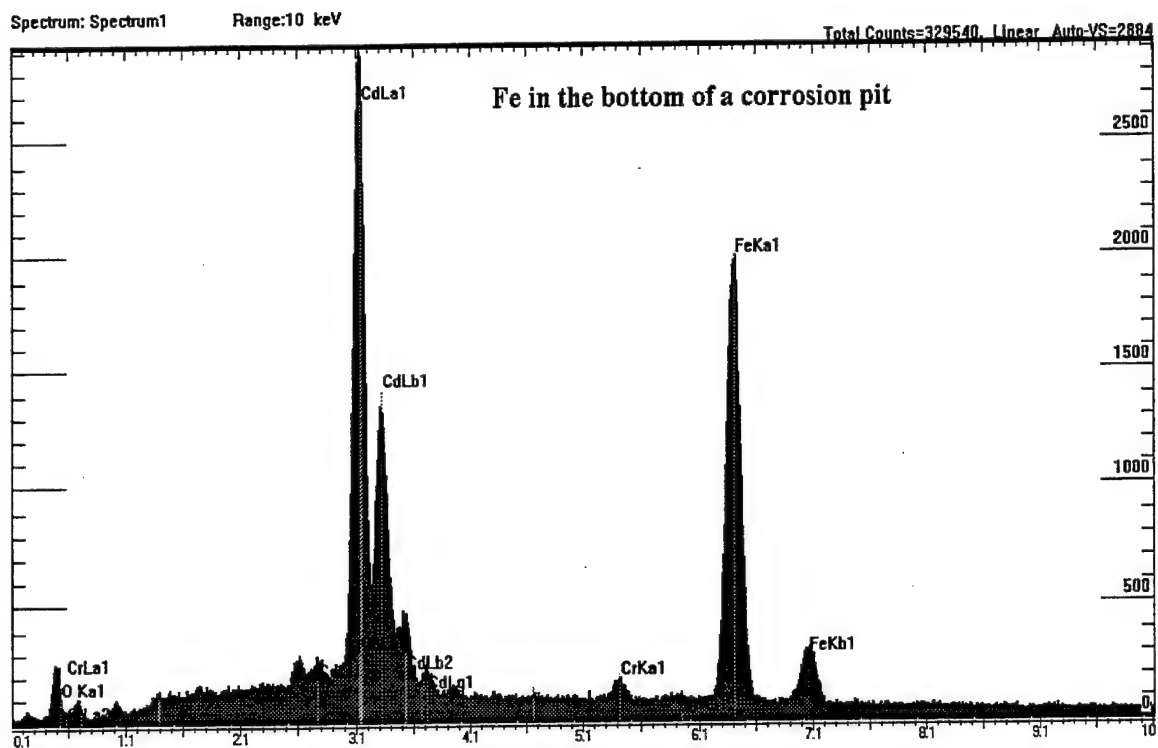


Figure 17. EDS Spectrum Showing Iron Within the Corrosion Pit.

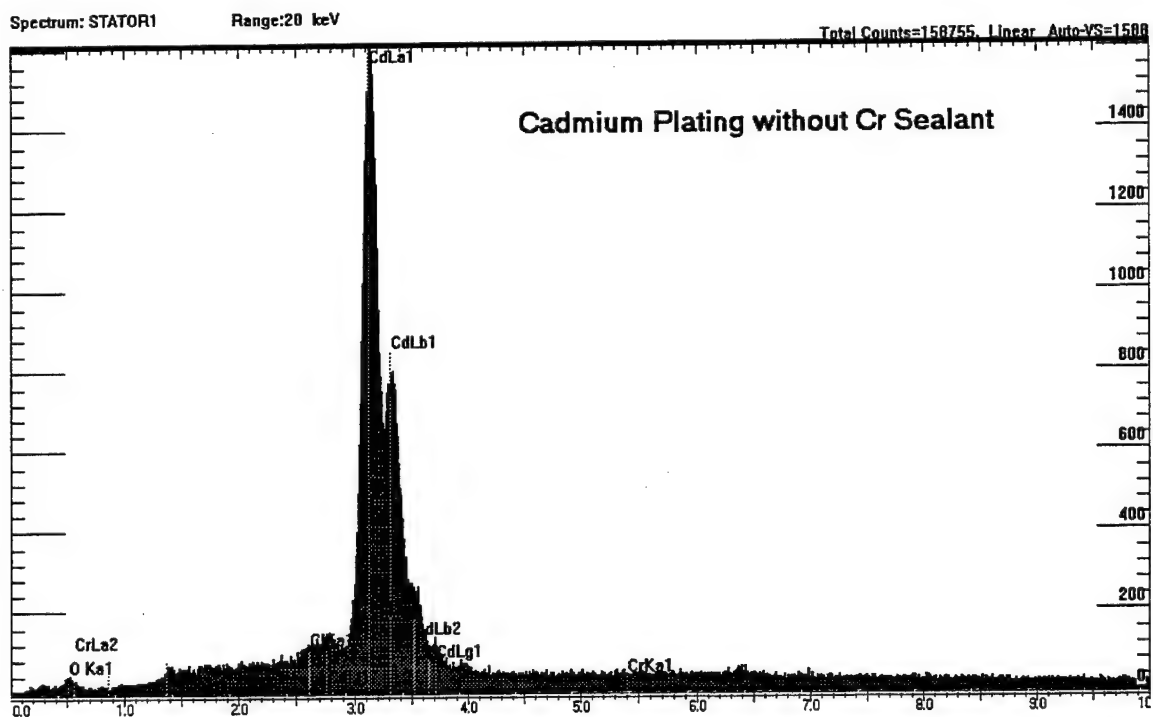


Figure 18. EDS Spectrum Displaying the Absence of Cr on the Stator Vane.

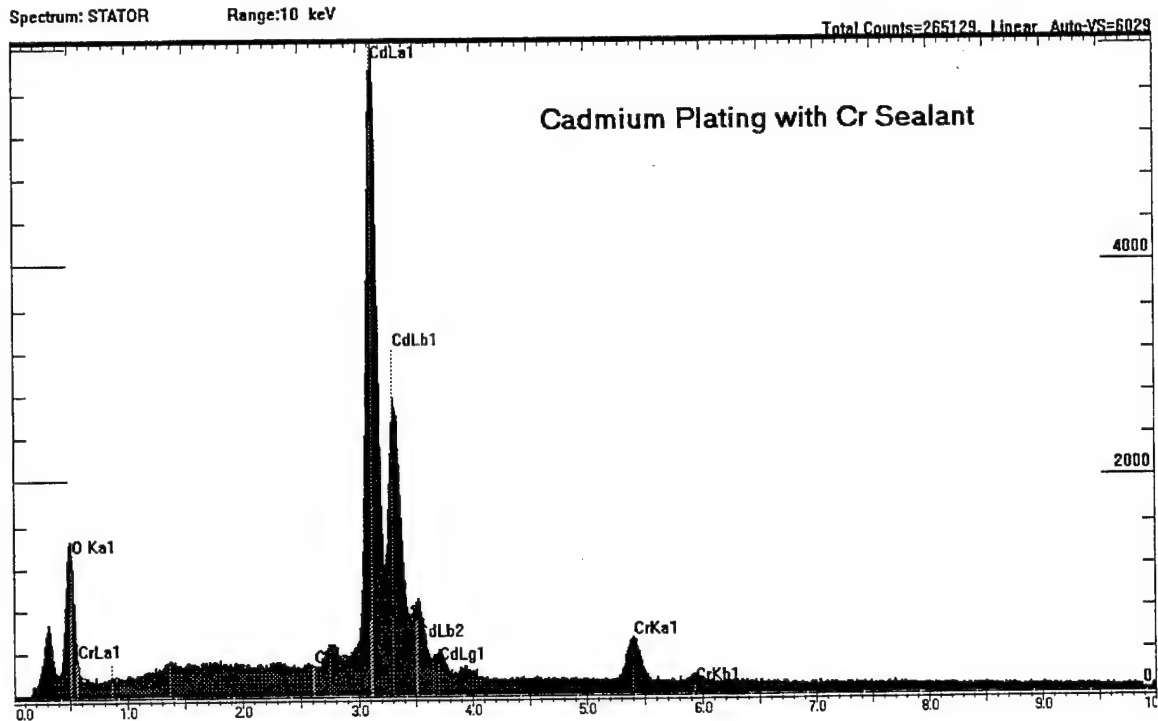


Figure 19. EDS Spectrum Showing a Detectable Cr Sealant on a Cadmium Nut.

corrosion was also the worst in the tightest corners where plating would be at a minimum. Regardless, EMI worked with their plating subcontractor and ARL-WMRD toward achieving a coating system that would pass the test.

3.8 Discussion. The cadmium plating specification AMS 2400, section 3.2.2, requires that the cadmium-plated components be immersed in a 3–5% chromic acid solution [2]. ARL-WMRD was not able to verify the existence of a chromate sealer applied over the cadmium plating. To further investigate this circumstance, ARL applied a chromic acid sealant over a section of the EMI component. Subsequently, EDS was performed to determine if chromium could be detected on the part after the “MacDermid Iridite 80” chromic acid sealant was applied. This solution was the same solution that Microfin Corp. purported to have used on the subject components. MacDermid provided the following sealing procedure.

- a. Running rinse.

- b. Alkaline aqueous cleaner wash.
- c. 1/4% nitric acid activation (5-s dip).
- d. Running rinse.
- e. Iridite 80 solution (5-s dip).
- f. Running rinse.
- g. Hot water rinse.
- h. Dry.

At the time of testing, MacDermid indicated that a 7% solution by volume of Iridite 80 would provide a 4% chromic acid solution. Investigation of this stipulation suggested that a 12% solution of Iridite 80 would provide a 4% chromic acid solution. The Material Safety Data Sheet (MSDS) states that the chromic acid concentration of Iridite 80 is 20–30%. Taking 25% as the average concentration, it would appear that a 12% solution of Iridite 80 provides a 4% chromic acid solution. However, at the time of testing, this was not discovered, and the 7% solution was utilized. The calculations utilized were:

Given: 12% Iridite by volume in water yields 4% chromic acid

$$7 \text{ vol.\% Iridite 80} \Rightarrow \frac{0.12}{0.04} = \frac{0.07}{X} \Rightarrow X = 2.33\% \text{ chromic acid}$$

This treatment provided the component with a rich, dark yellow color. Subsequent EDS testing verified that chromium could easily be detected on the yellow sealed surface. It was readily observable that this sealing operation was not performed on the EMI component, since

the color was not yellow, but, instead, was the gray color of bare cadmium plating. ARL surmised that a weaker concentration could have been utilized by EMI. Therefore, in addition to the 7% Iridite 80 concentration, ARL utilized the minimum concentration recommended by MacDermid for sealing cadmium-plated parts. This concentration was 1.25% by volume Iridite 80 in water. The same sealing procedure, as outlined previously, was utilized. There was no significant color change of the part. It remained the traditional gray color of cadmium plate. Subsequent EDS testing, however, verified the existence of chromium on the surface, similar to Figure 19. These results indicated that after exposure to the minimum suggested (1.25%) chromic acid dip utilizing the product, Iridite 80, a detectable chromium layer was present on the subject components.

4. Phase Two – Stator Modification

As a result, EMI sent a new stator section with a revised corrosion-resistant coating system. This coating, however, also appeared a bright, shiny silver color, indicative of pure cadmium. It was quite evident that the Microfin Corporation cadmium plating process had been altered. The present component was much more shiny and reflective than the dull gray of the previously examined component. The characteristic bronze or iridescent yellow hue of a chromic acid sealer was still not noticeable. However, a weak concentration solution combined with short immersion times (producing a thinner coating) may have been used, resulting in a clear chromic acid coating. In general, the coating was smooth, continuous, adherent to the basis metal, uniform in appearance, and essentially free from defects that did satisfy the quality appearance requirements of AMS 2400, section 3.5 [2].

4.1 Corrosion Testing. The most recently received assembly was tested side by side against sections from the old component that had been chromic acid dipped (0.42% chromic acid, the minimum recommended by the manufacturer, and 2.33% chromic acid) according to the suggestions of MacDermid. Figures 20 and 21 depict a section of the new stator before salt fog testing. Figures 22 and 23 show the old component that had been dipped in 0.42% chromic acid for comparison. The extremely bright shiny cadmium coating on the new stator can be directly

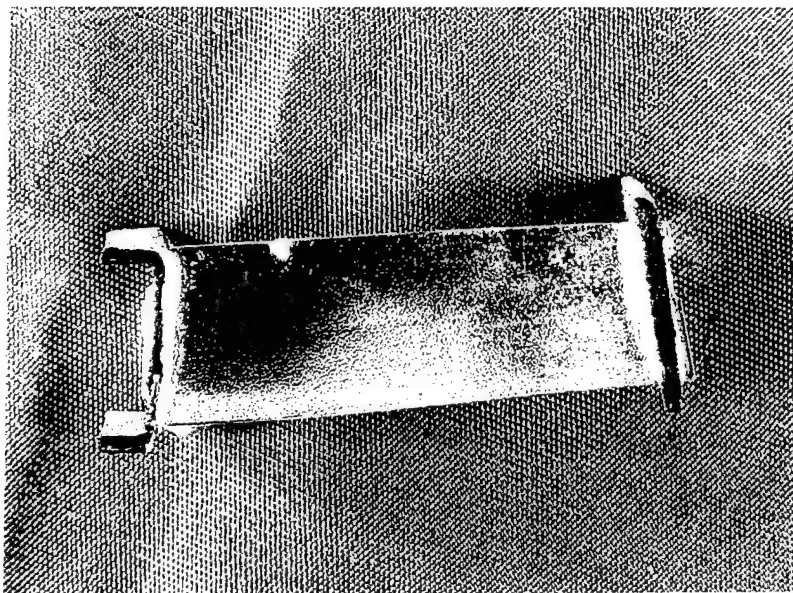


Figure 20. New Section of the Stator Vane, Concave Side (Magnified 1.5×).

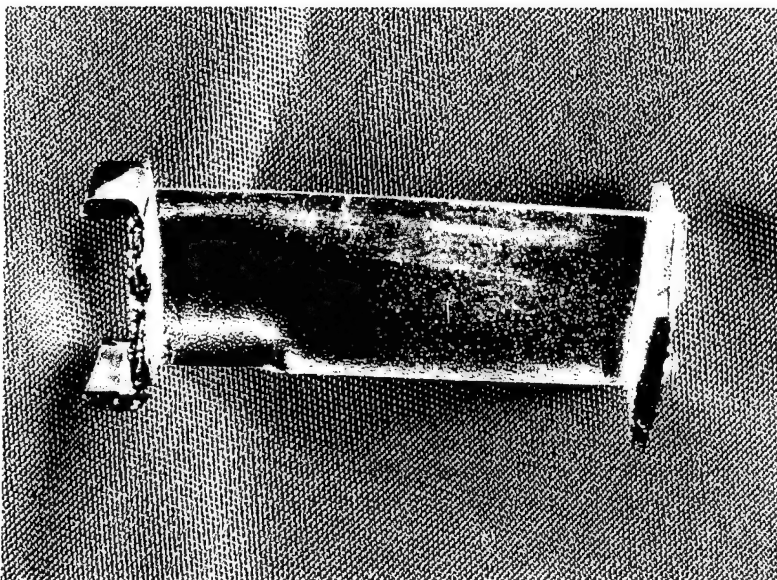


Figure 21. New Section of the Stator Vane, Convex Side (Magnified 1.5×).

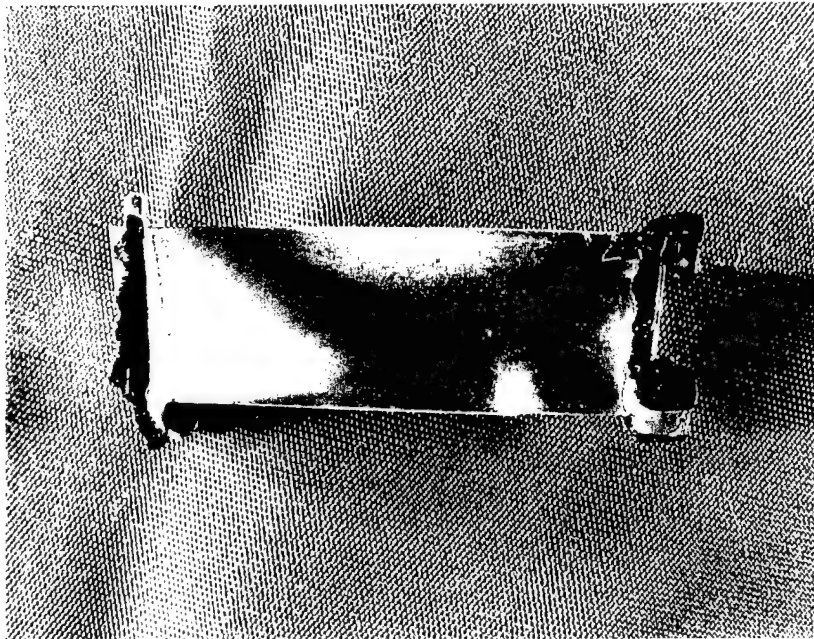


Figure 22. Previous 0.42% Dipped Stator, Concave Side (Magnified 1.5×).

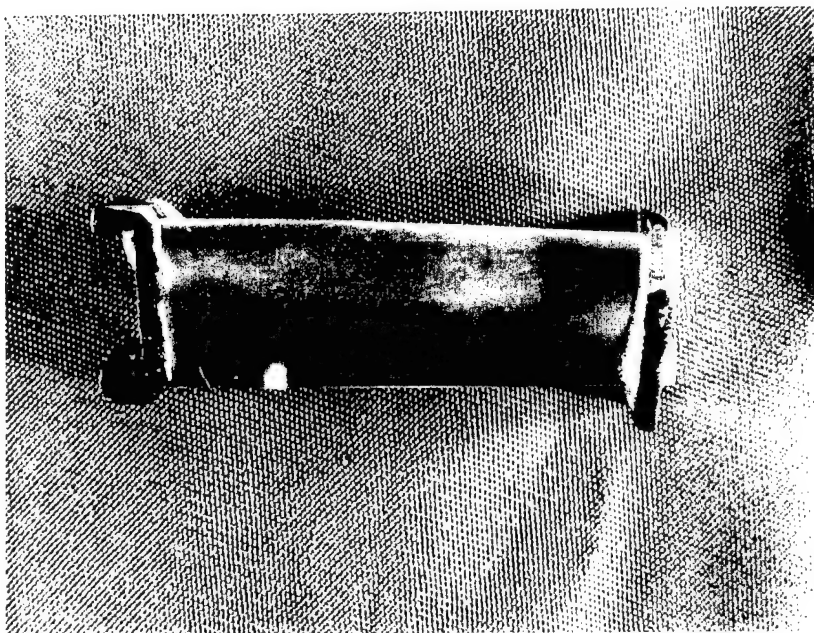


Figure 23. Previous 0.42% Dipped Stator, Convex Side (Magnified 1.5×).

contrasted with the dull gray previous coating in Figure 24. Figures 25–27 depict a section of the old stator after 2.33% chromic acid immersion, where the yellow tint can clearly be observed.

Figures 28–31 show the new and old (0.42% dipped) stator section after 24 hr of salt fog exposure per ASTM-B-117, respectively (compare with Figures 20–23). Even with the new cadmium coating, the performance of the 0.42% chromic acid dipped stator is superior after 24 hr exposure.

Figure 32 compares the new and old (0.42% dipped) stator sections showing the inner shroud braze area. Both stator sections show only some white cadmium oxide product. No reddish-orange corrosion of the steel is present. Figures 33–35 show that the old (2.33% dipped) stator shows no significant corrosion at all, after 24 hr salt fog exposure.

After 200 hr exposure per ASTM-B-117, the new stator exhibited significant white product along the vane and severe pitting within the braze area, as shown in Figures 36 and 37. Figures 38 and 39 depict the corrosive action on the 0.42% dipped old stator and general corrosion can be observed. This general corrosion was more representative of the previous results obtained. However, the area of corrosion seemed to be limited to the inner shroud braze area. Comparative macrographs of the new stator vs. the old 0.42% dipped stator are shown in Figures 40 and 41. After 200 hr of exposure, general corrosion of the 0.42% dipped stator was observable near the inner shroud brazed area and pitting was observable on the new corrosion system stator. It could not be determined which corrosion-resistant coating performed better. Neither would pass the corrosion requirements established in AMS 2400 Rev. S [2].

Figures 42–44 depict the 2.33% dipped old stator after 200 hr of salt fog exposure per ASTM-B-117. Some slight corrosion was evident along the braze and inner shroud. However, this section appeared to completely inhibit the white cadmium oxide product from forming and looked the best in comparison to the other sections.

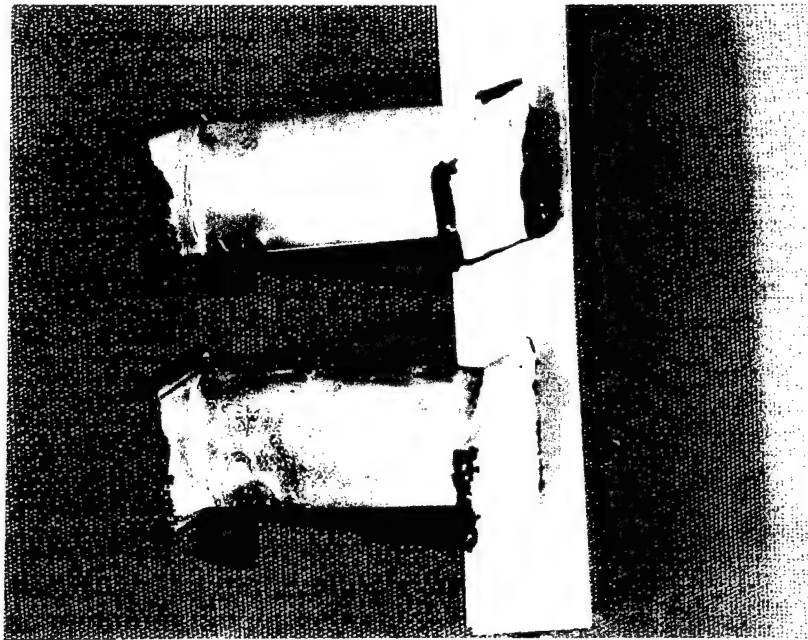


Figure 24. Previous 0.42% Dipped and New Stator Sections (Magnified 1.5×).

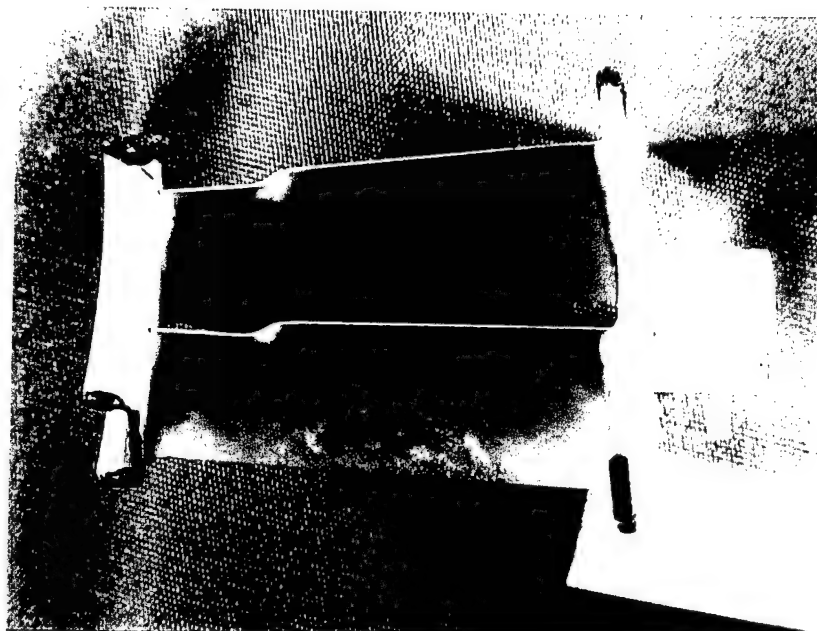


Figure 25. Previous 2.33% Dipped Stator Section, Concave Side (Magnified 1.5×).

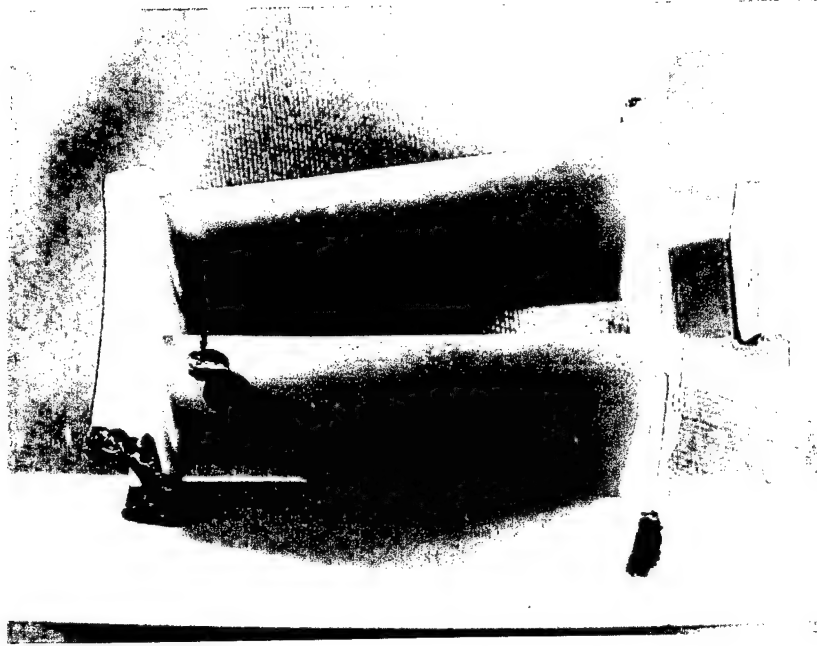


Figure 26. Previous 2.33% Dipped Stator Section, Convex Side (Magnified 1.5×).

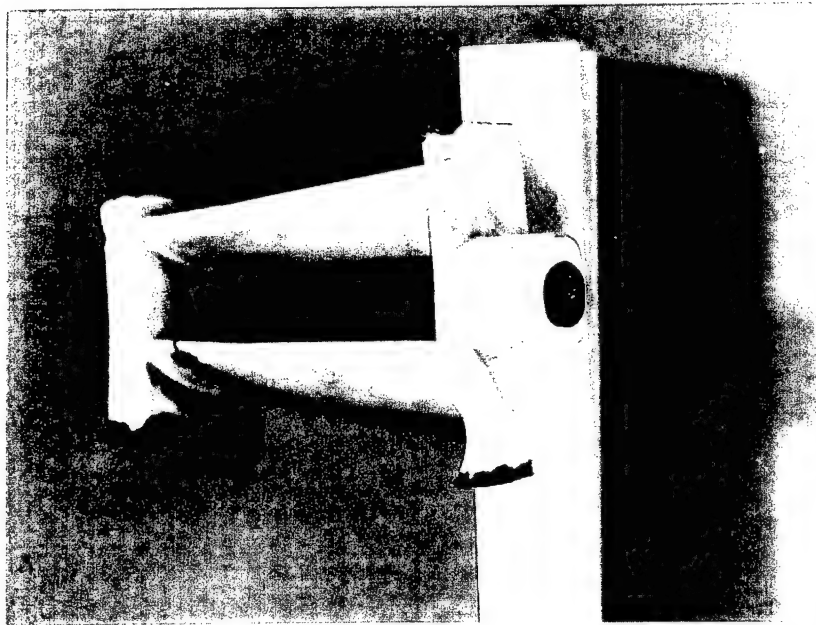


Figure 27. Previous 2.33% Dipped Stator Section, Braze Area (Magnified 1.5×).

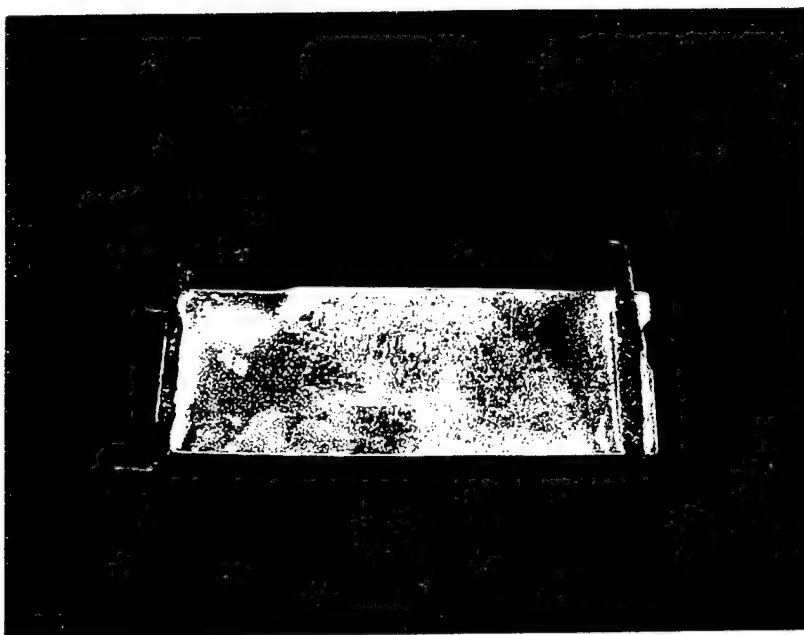


Figure 28. New Stator Section After 24 hr Salt Fog Exposure, Concave Side (Magnified 1.5 \times).

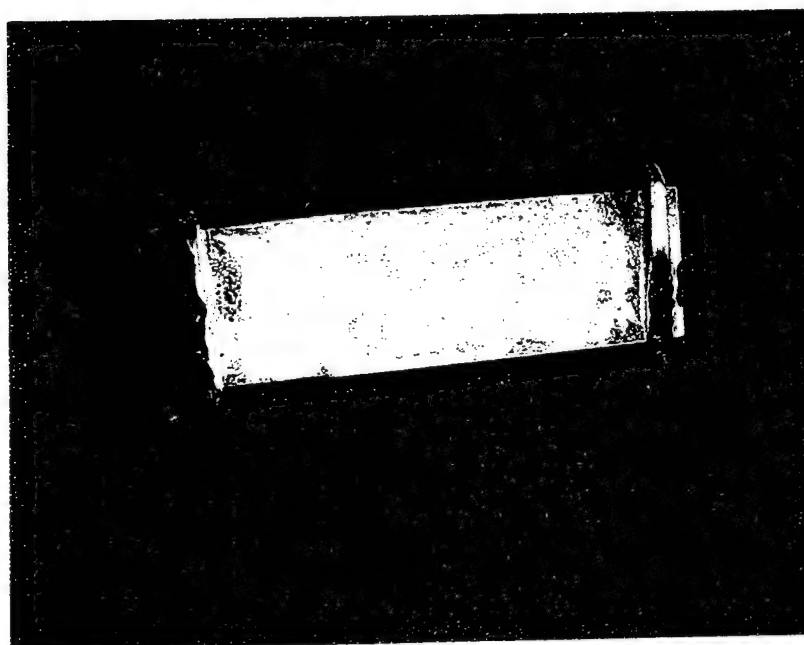


Figure 29. New Stator Section After 24 hr Salt Fog Exposure, Convex Side (Magnified 1.5 \times).

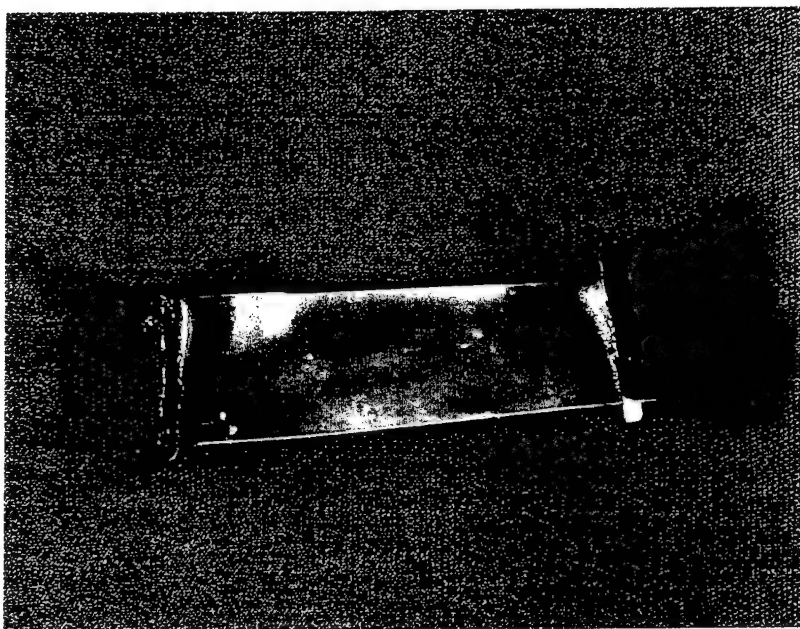


Figure 30. 0.42% Dipped Stator After 24 hr Salt Fog Exposure, Concave Side (Magnified 1.5×).

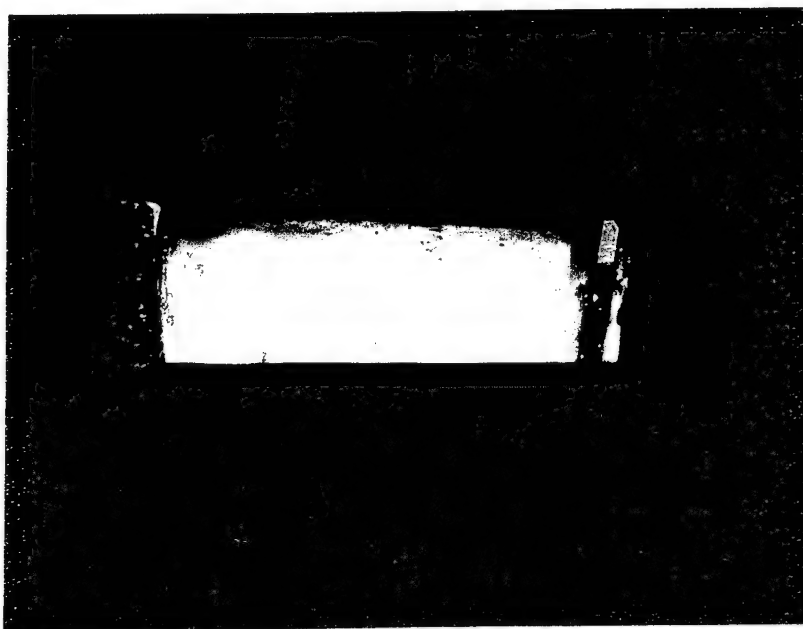


Figure 31. 0.42% Dipped Stator After 24 hr Salt Fog Exposure, Convex Side (Magnified 1.5×).

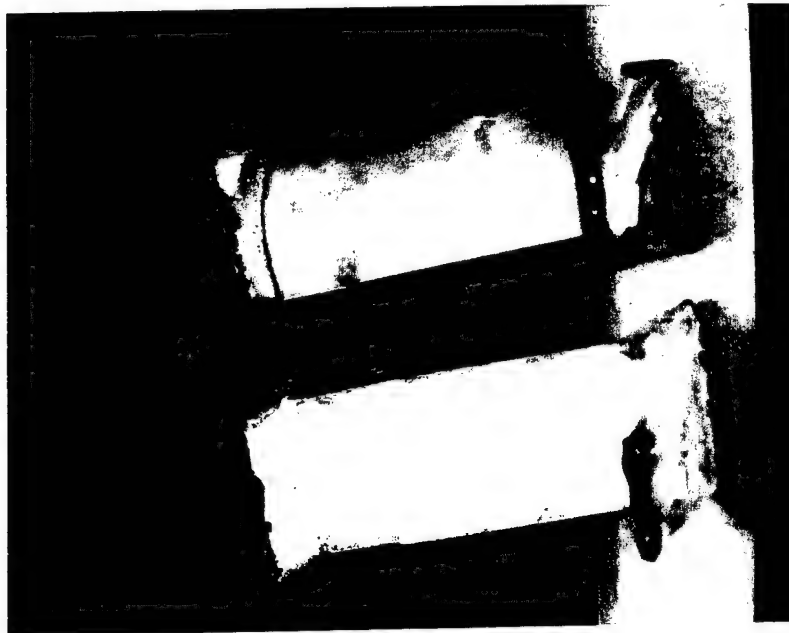


Figure 32. 0.42% Dipped and New Stator After 24 hr Salt Fog Exposure, Braze (Magnified 1.5 \times).

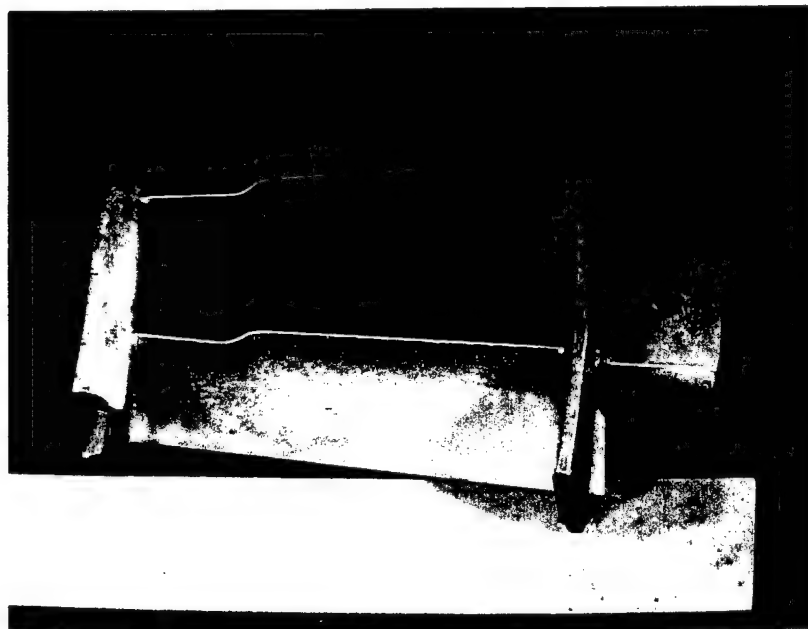


Figure 33. 2.33% Dipped Stator After 24 hr Salt Fog Exposure, Concave Side (Magnified 1.5 \times).

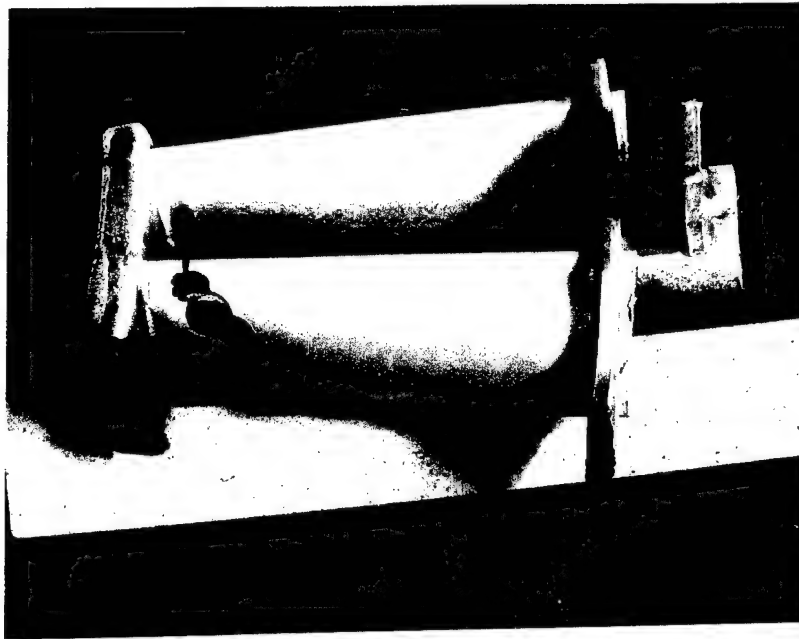


Figure 34. 2.33% Dipped Stator After 24 hr Salt Fog Exposure, Convex Side (Magnified 1.5×).

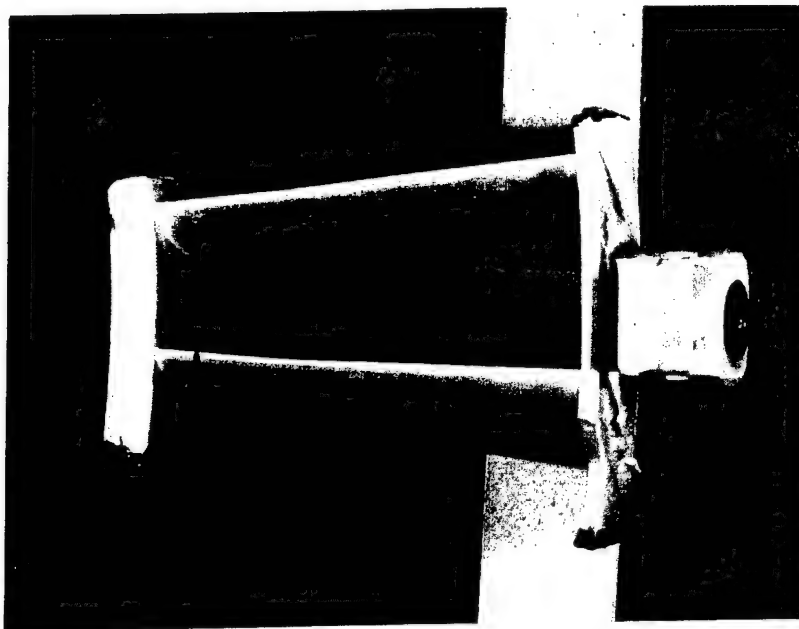


Figure 35. 2.33% Dipped Stator After 24 hr Salt Fog Exposure, Braze Area (Magnified 1.5×).

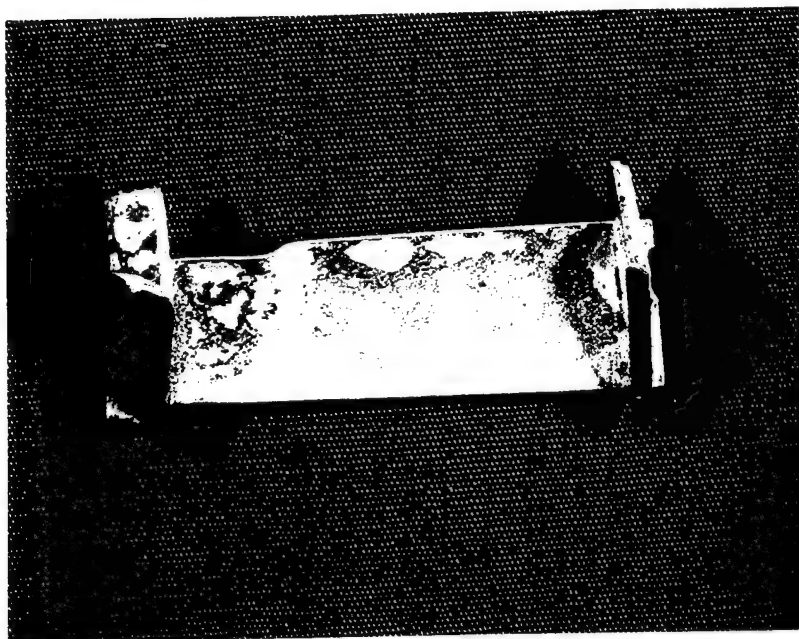


Figure 36. New Stator Section After 200 hr Salt Fog Exposure, Concave Side (Magnified 1.5 \times).

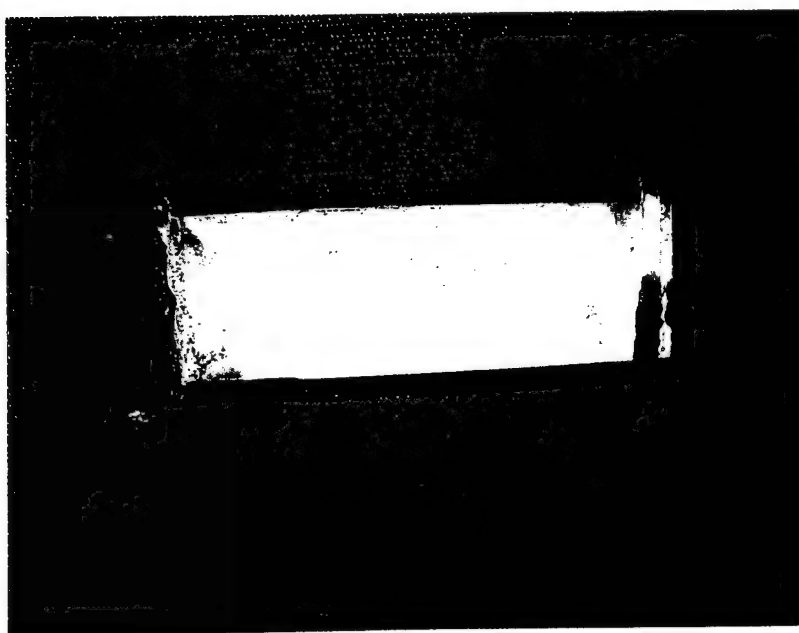


Figure 37. New Stator Section After 200 hr Salt Fog Exposure, Convex Side (Magnified 1.5 \times).

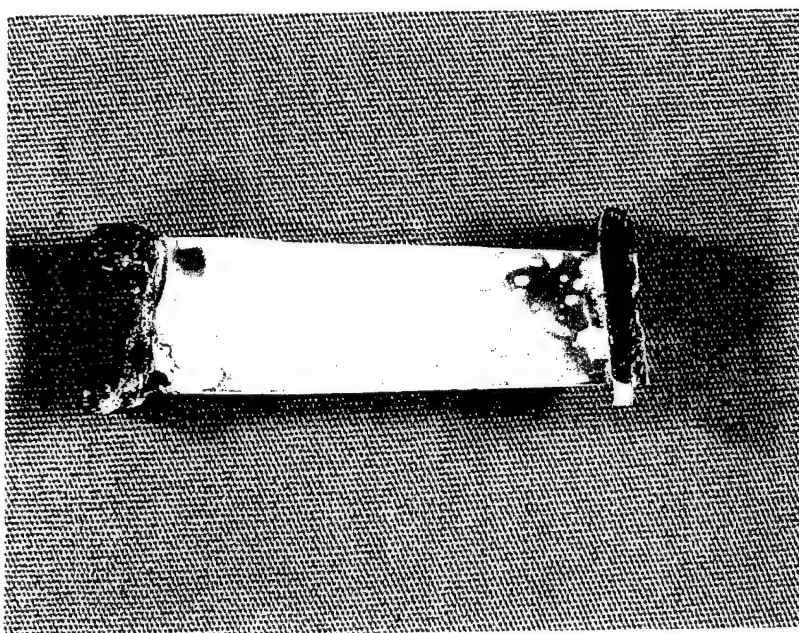


Figure 38. 0.42% Dipped Stator After 200 hr Salt Fog Exposure, Concave Side (Magnified 1.5×).

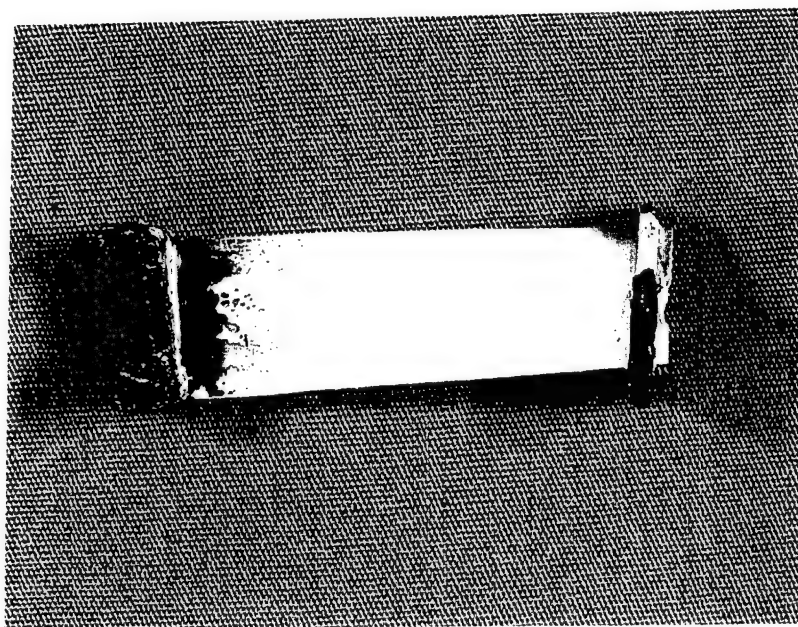


Figure 39. 0.42% Dipped Stator After 200 hr Salt Fog Exposure, Convex Side (Magnified 1.5×).

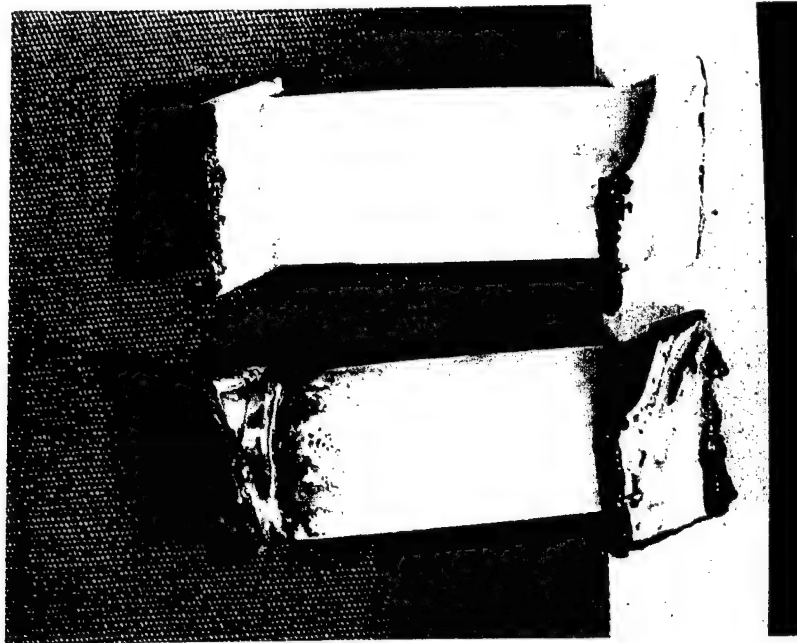


Figure 40. 0.42% Dipped and New Stator Sections After 200 hr Salt Fog Exposure, Convex Side, Braze Area (Magnified 1.5 \times).

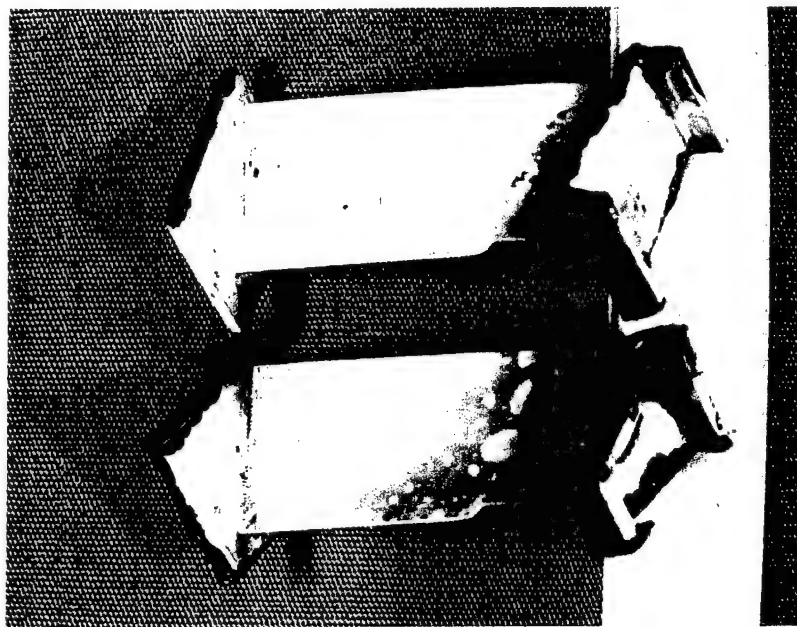


Figure 41. 0.42% Dipped and New Stator Sections After 200 hr Salt Fog Exposure, Concave Side, Braze Area (Magnified 1.5 \times).

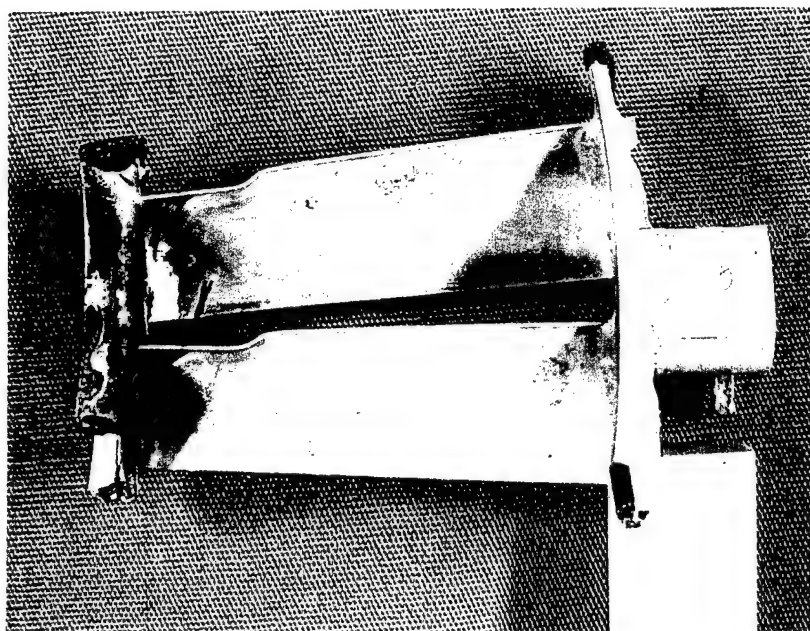


Figure 42. 2.33% Dipped Stator After 200 hr Salt Fog Exposure, Concave Side (Magnified 1.5 \times).

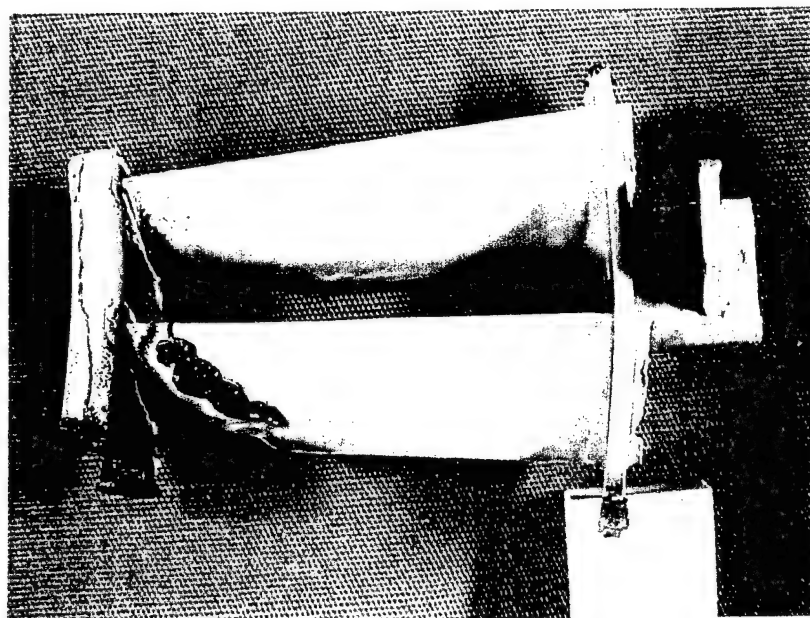


Figure 43. 2.33% Dipped Stator After 200 hr Salt Fog Exposure, Convex Side (Magnified 1.5 \times).

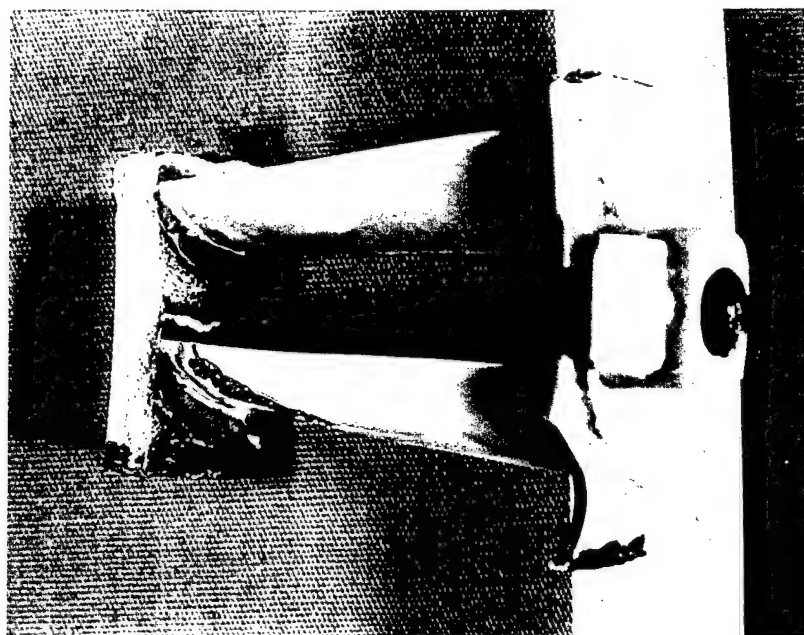


Figure 44. 2.33% Dipped Stator After 200 hr Salt Fog Exposure, Braze Area (Magnified 1.5 \times).

In contrast, the severe pits formed on the new stator section can be seen in Figures 45–47. These pits appeared to originate in the braze area and were extremely deep. This severe corrosion would constitute failure of the salt fog exposure requirement. The 0.42% dipped old stator section would also have failed this requirement due to the significant amount of general corrosion observed. The 2.33% chromic acid dipped component possibly might have passed the exposure test (if it were under scrutiny). The chromic acid treatments appeared to have greatly increased the performance of the components in the salt fog exposure testing even though they were below the concentration required by the governing specifications. Note that the governing specification, AMS 2400 Rev. S calls out a 3–5% chromic acid immersion to seal the cadmium plating [2].

4.2 Coating Thickness. Similar cross sections of several vanes were prepared metallographically and examined per ASTM-B-487, as previously discussed [5]. Figure 48 shows a representative area along the convex side of a vane near the inner shroud where the cadmium plating was approximately 0.00065 in thick. In contrast, Figure 49 is indicative of the

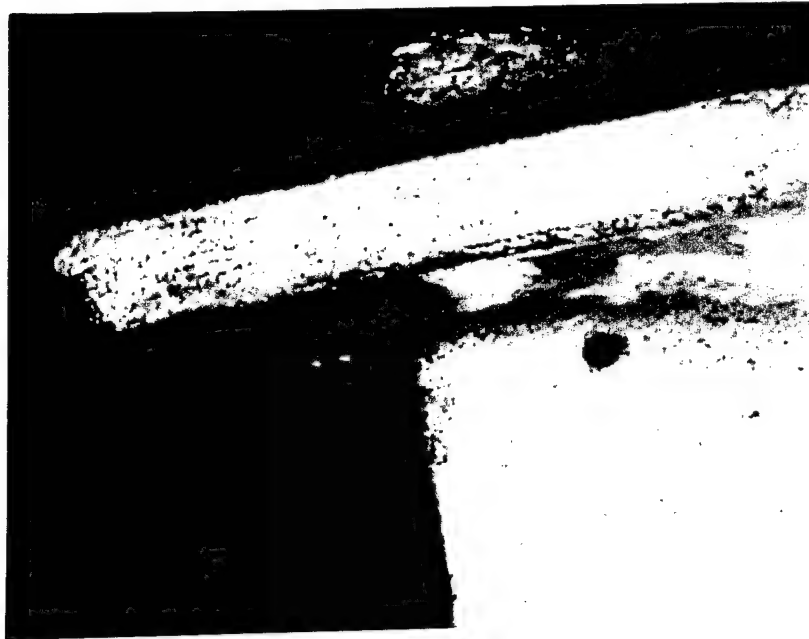


Figure 45. New Stator Section Showing a Corrosion Pit (Magnified 1.5×).

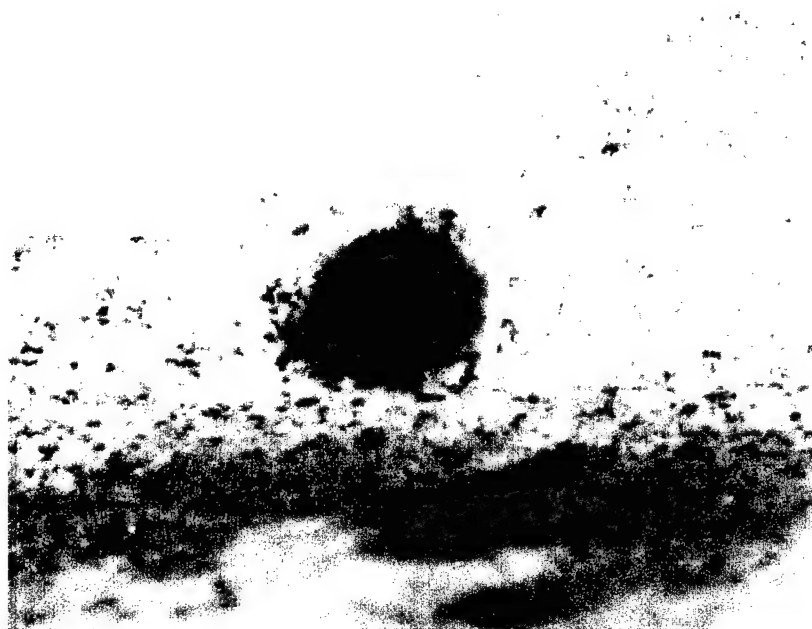


Figure 46. Higher Magnification of the New Stator in Figure 26 (Magnified 75×).



Figure 47. New Stator Section Showing Multiple Corrosion Pits (Magnified 75 \times).

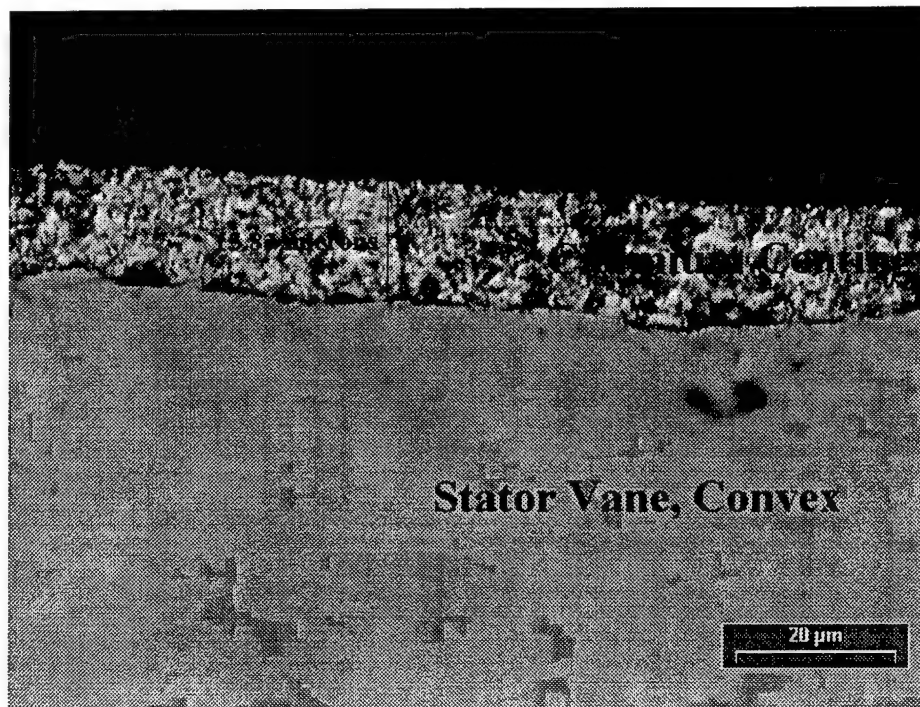


Figure 48. Cadmium Plating Thickness of New Stator Near Inner Shroud, Convex Side.

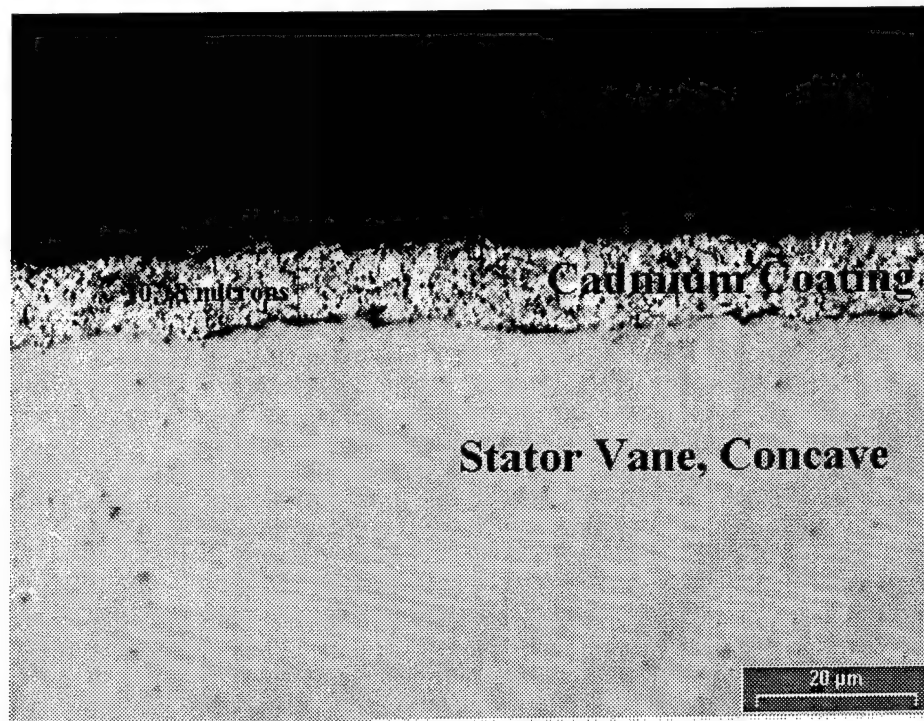


Figure 49. Cadmium Plating Thickness of New Stator Near Inner Shroud, Concave Side.

cadmium plating observed on much of the concave side of a vane near the inner shroud where the thickness was approximately 0.00043 in.

The results showed that the cadmium coating thickness was adequate in all locations. In general, the cadmium was approximately twice the thickness of the original part, indicative of a change in the cadmium plating process. This would also account for the vast increase in performance under salt fog exposure, even though the component still failed according to the governing requirement. Table 2 presents the cadmium thickness measurements, including the locations taken on the part (contrast the measurements presented in Table 1).

4.3 SEM/EDS Examination. Portions of the sectioned components were examined by SEM. Similar to Phase I, the dark areas of corrosion were verified to be pits containing a significant amount of corrosion product. A cadmium plating was detectable on all surfaces. Again, an attempt was made to verify the existence of a chromate sealer over the cadmium coating. This sealer would be evidenced by the presence of the element chromium (Cr) within

Table 2. Recoated Stator Cadmium Plating Thickness

Component	Location	Measurement (mils)
<u>Shrouds</u>	Outer Shroud	0.62, 0.72 ^a
	Inner Shroud	0.66, 0.37 ^a
<u>Vanes</u>		
• Near Outer Shroud	Concave Side	0.50
	Convex Side	0.64
• Middle of Vane	Concave Side	0.62
	Convex Side	0.76
• Near Inner Shroud	Concave Side	0.43
	Convex Side	0.65

^a Indicates the measurement was taken more than once.

the EDS spectrum, as previously discussed. The element was not observed above the background of the EDS spectrum. Figure 18 depicts a similar EDS spectrum showing the absence of chromium over cadmium plating. Typically, chromated and chromic-acid-treated components do contain measurable amounts of Cr. These findings show either the sealer was absent or below detectable limits. In either case, the corrosion protection afforded would be minimized. This minimal protection was demonstrated under salt fog exposure. The old section with 2.33% chromic acid treatment nearly outperformed the recoated section that had almost twice the cadmium coating thickness and no detectable chromate or chromic acid treatment.

The results demonstrated the importance of a reasonable chromate sealer over the cadmium plate. Other researchers have presented similar results in open literature. The significance of chromate sealing has been widely documented and accepted. EMI Incorporated agreed to evaluate an iridescent yellow chromic acid sealed part but still insisted that the component would never pass the salt fog requirement of AMS 2400 without changes to the wording of the requirement. Subsequently, a T-55 engine stator vane segment, supplied by Electro-Methods Incorporated and received by ARL-WMRD, was evaluated for corrosion resistance, coating thickness, and for visual quality. This stator section had a revised corrosion-resistant coating

system that included an iridescent yellow chromate sealant applied over a 0.0005-in (approximate) cadmium layer. This section was a previously examined sample that had been stripped of its original coating system and recoated.

5. Phase Three – Design Finalization

5.1 Visual Inspection. The section of the stator vane, when viewed with the naked eye, exhibited a bright shiny yellowish color, indicative of chromate or chromic acid sealed cadmium. It was evident that the cadmium plating process had again been changed since the examination of the last stator section. The present component had a yellowish tint rather than the reflective gray color of the previously examined component. The characteristic bronze or iridescent yellow hue of a chromic acid or chromate sealer was evident. In general, the coating was smooth, continuous, adherent to the basis metal, uniform in appearance, and essentially free from defects. This component again passed the visual quality requirements of AMS 2400 Rev. S [2].

5.2 Corrosion Testing. The most recently received stator section was salt fog tested in accordance with ASTM-B-117. Figures 50 and 51 depict the concave and convex sides of the section before salt fog testing, respectively. Figures 52 and 53 show the inner shroud vane braze area with more clarity, also prior to salt fog exposure. The yellow iridescent hue of a chromium sealer is clearly evident.

Figures 54–57 depict the stator section after 24 hr salt fog exposure (compare with Figures 50–53). The chromium sealer is still evident even after 24 hr of exposure. There was no white cadmium oxide product visible on the section.

After 200 hr exposure, the new stator barely exhibited any significant white product along the vane and no pitting within the braze area, as shown in Figures 58–61. Only some small water spots on the convex side of the vane were evident.

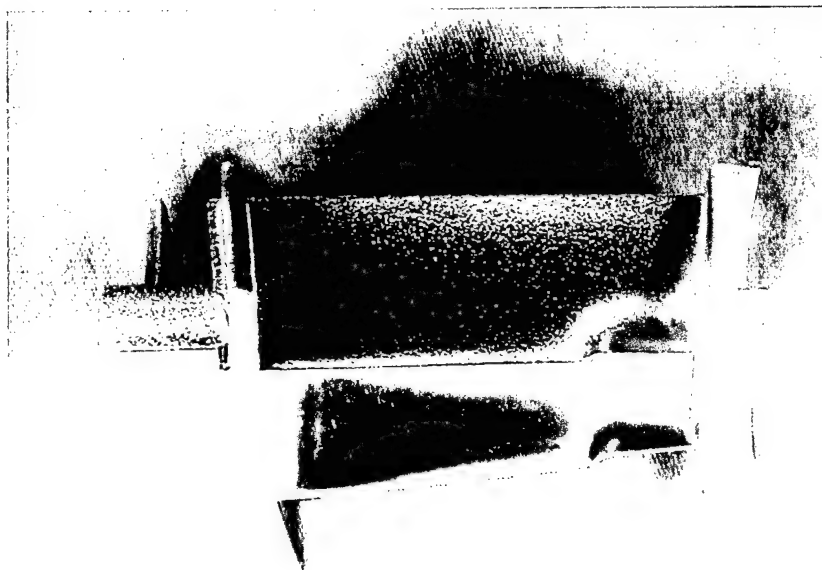


Figure 50. Replated Section of the Stator Vane, Concave Side (Magnified 1.5×).

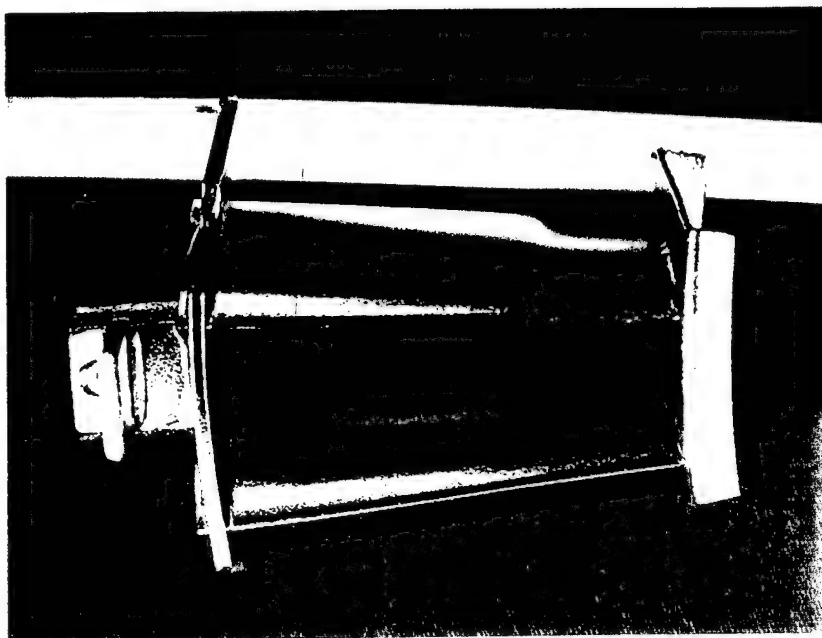


Figure 51. Replated Section of the Stator Vane, Convex Side (Magnified 1.5×).

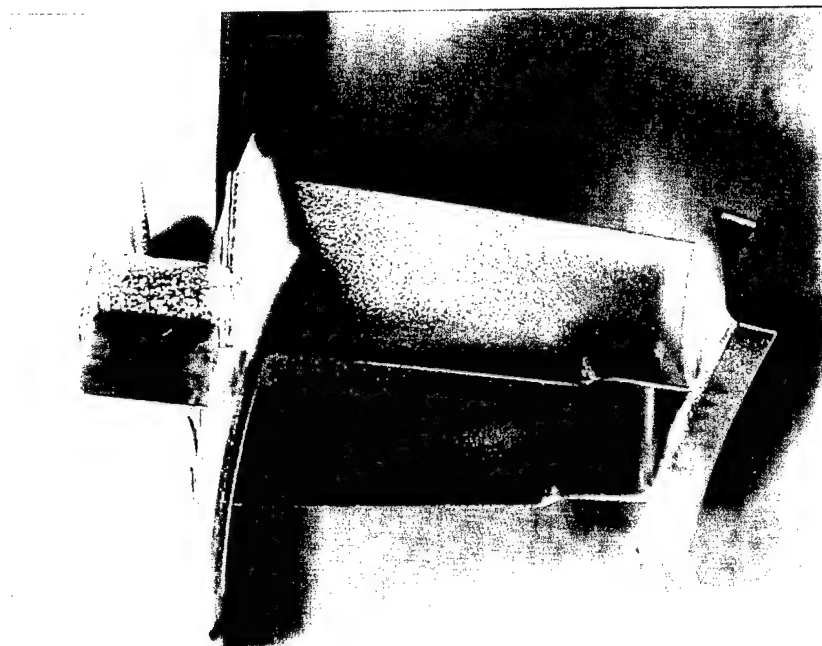


Figure 52. Replated Stator Section, Braze Area, Concave Side (Magnified 1.5×).

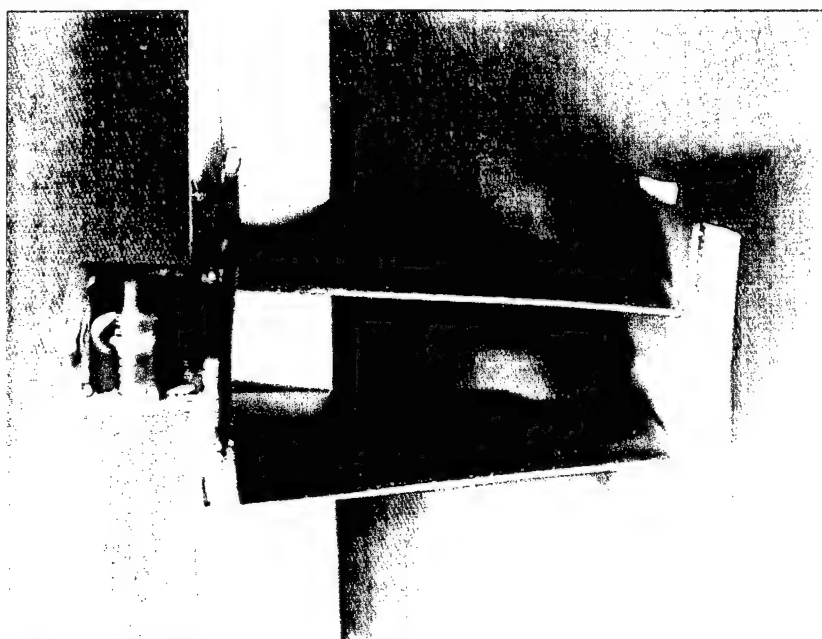


Figure 53. Replated Stator Section, Braze Area, Convex Side (Magnified 1.5×).

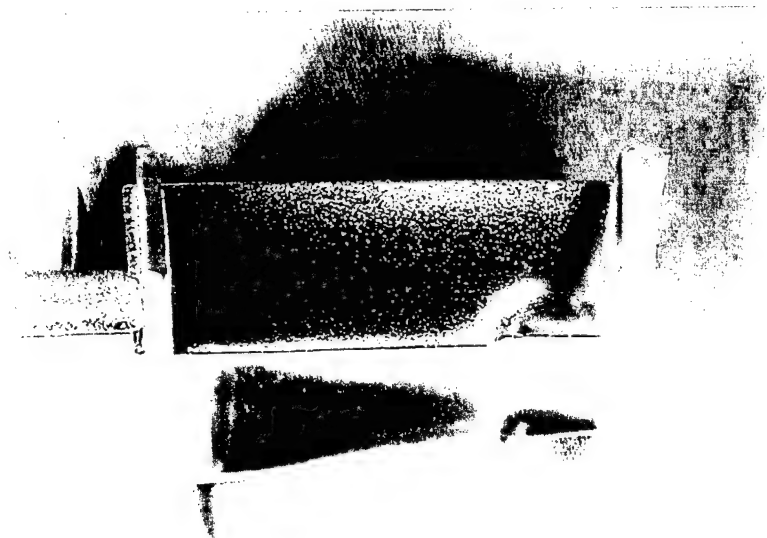


Figure 54. 24 hr Salt Fog Exposure of the Stator, Concave Side (Magnified 1.5×).

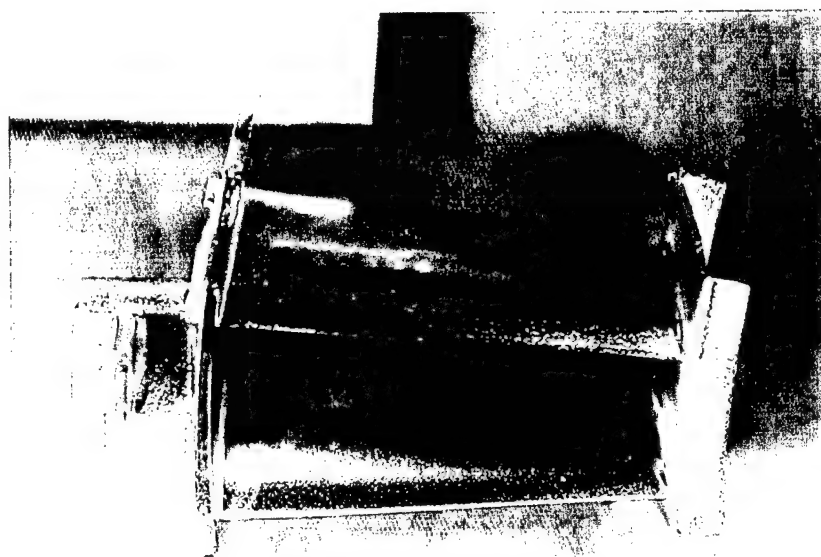


Figure 55. 24 hr Salt Fog Exposure of the Stator, Convex Side (Magnified 1.5×).

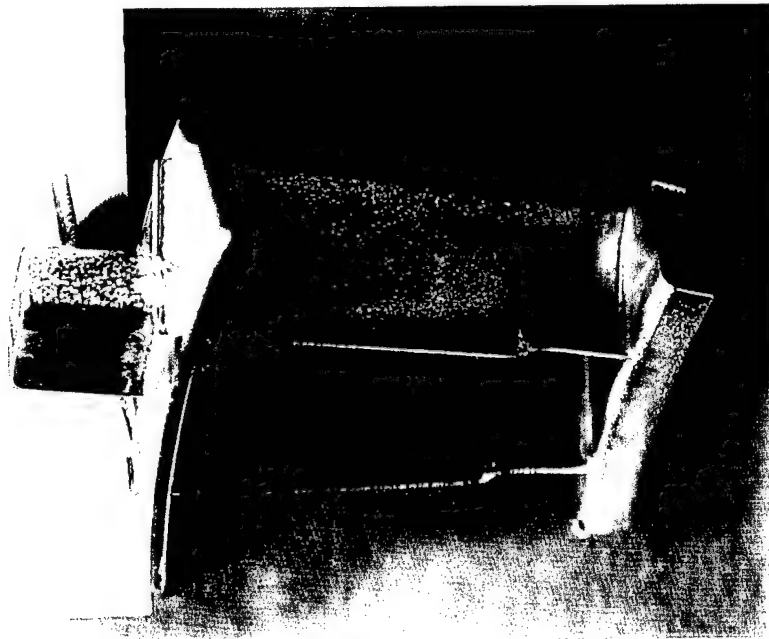


Figure 56. 24 hr Salt Fog Exposure, Braze Area, Concave Side (Magnified 1.5×).

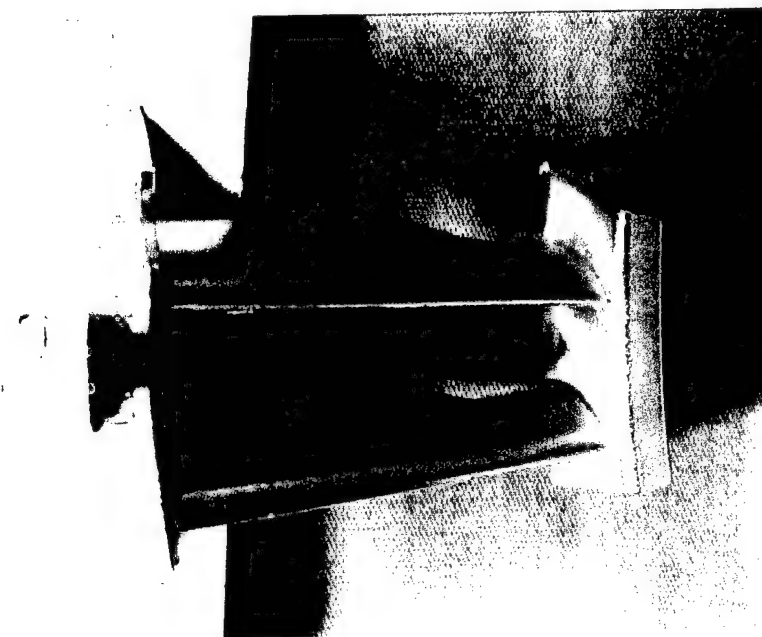


Figure 57. 24 hr Salt Fog Exposure, Braze Area, Convex Side (Magnified 1.5×).

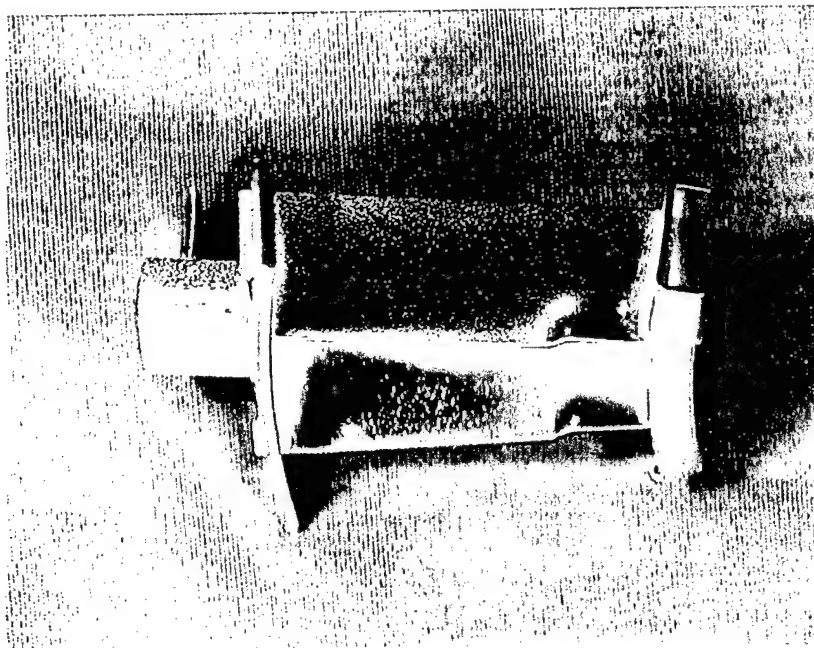


Figure 58. 200 hr Salt Fog Exposure of the Stator, Concave Side (Magnified 1.5x).

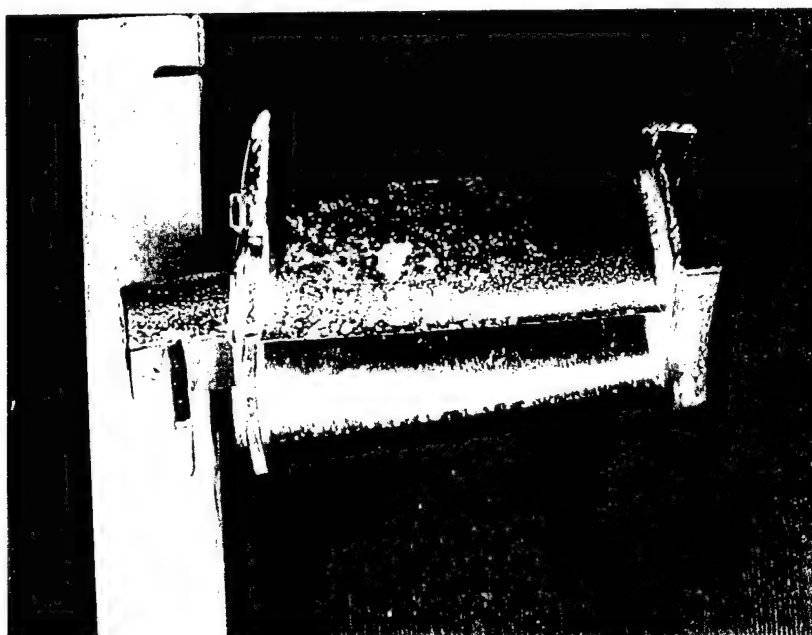


Figure 59. 200 hr Salt Fog Exposure of the Stator, Convex Side (Magnified 1.5x).

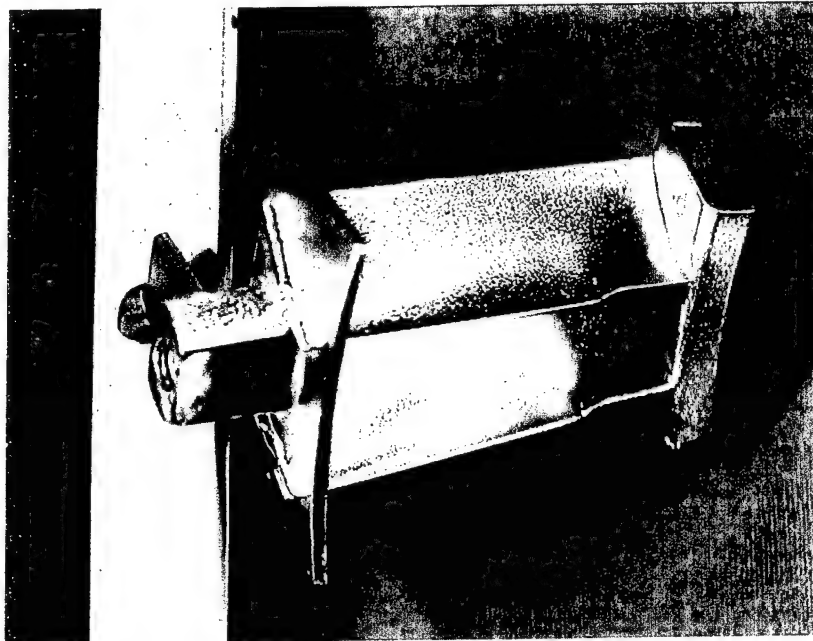


Figure 60. 200 hr Salt Fog Exposure, Braze Area, Concave Side (Magnified 1.5×).

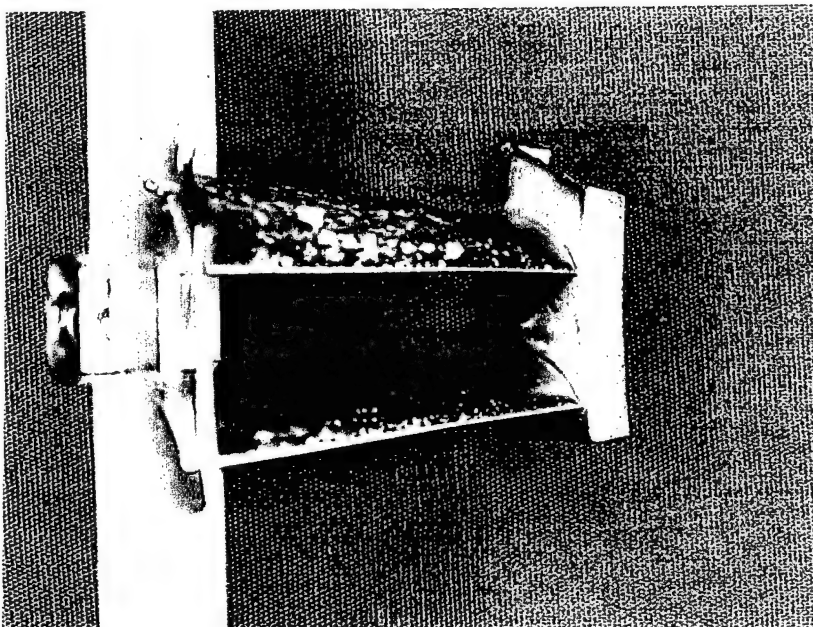


Figure 61. 200 hr Salt Fog Exposure, Braze Area, Convex Side (Magnified 1.5×).

Figure 62 shows the inside edge of the inner shroud where significant corrosion had occurred on previous samples. No corrosion was visible on this stator section. After the 200-hr exposure period, the yellow hue had started to fade but was still evident. The chromic acid treatment appeared to have greatly increased the performance of the components under salt fog exposure testing, as expected. This stator section's corrosion resistance satisfied the requirements of the governing specification.

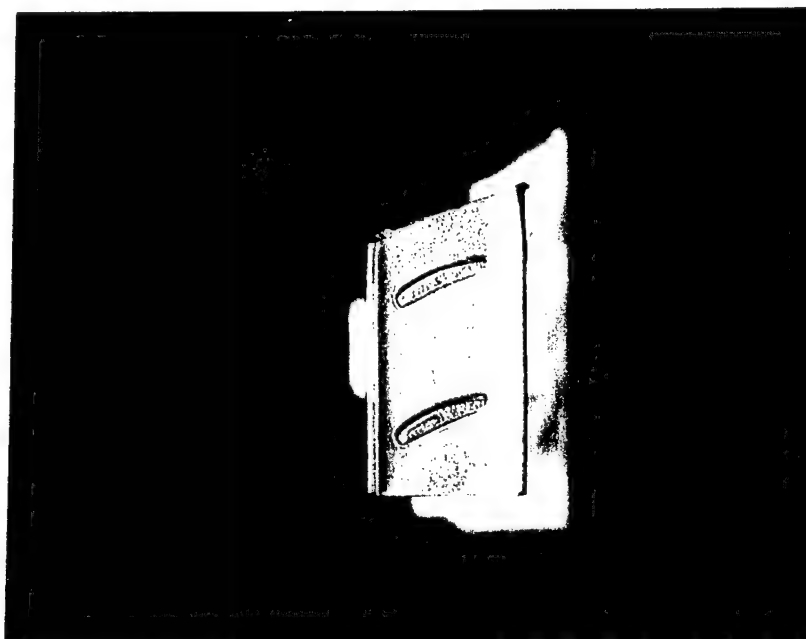


Figure 62. Inside Edge of Inner Shroud Showing Brazed Vanes (Magnified 1.5×).

5.3 Sectioning. The stator vane was sectioned after corrosion salt fog experiments to create several cross sections for cadmium coating thickness measurements. A sectioning diagram (Figure 63) is provided as follows:

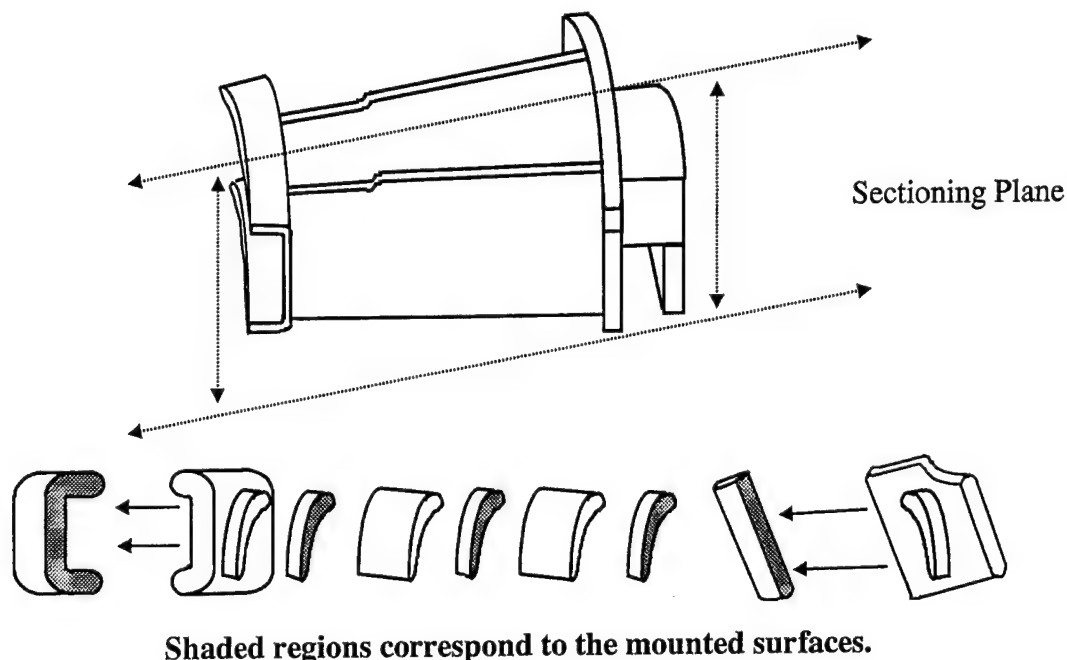


Figure 63. Diagram of Sectional Stator Vane.

5.4 Coating Thickness. Cross sections of several vanes were prepared metallographically and examined per ASTM-B-487. Figure 64 shows a representative area along the convex side of a vane near the middle where the cadmium plating was approximately 0.00054 in thick. In contrast, Figure 65 is indicative of the cadmium plating observed on much of the concave side of a vane near the middle where the thickness was approximately 0.00043 in.

The measurement results show that the cadmium coating thickness was adequate in all locations. Table 3 presents the cadmium thickness measurements, including the locations, taken on the part.

5.5 SEM/EDS Examination. Portions of the sectioned components were examined by SEM. A cadmium plating was detectable on all surfaces. Verification of the existence of a chromate or chromic acid sealer over the cadmium coating was performed with the EDS system. This was evidenced by the presence of the element chromium (Cr) within the EDS spectrum. Figure 66 depicts the EDS spectrum from the new stator vane section.

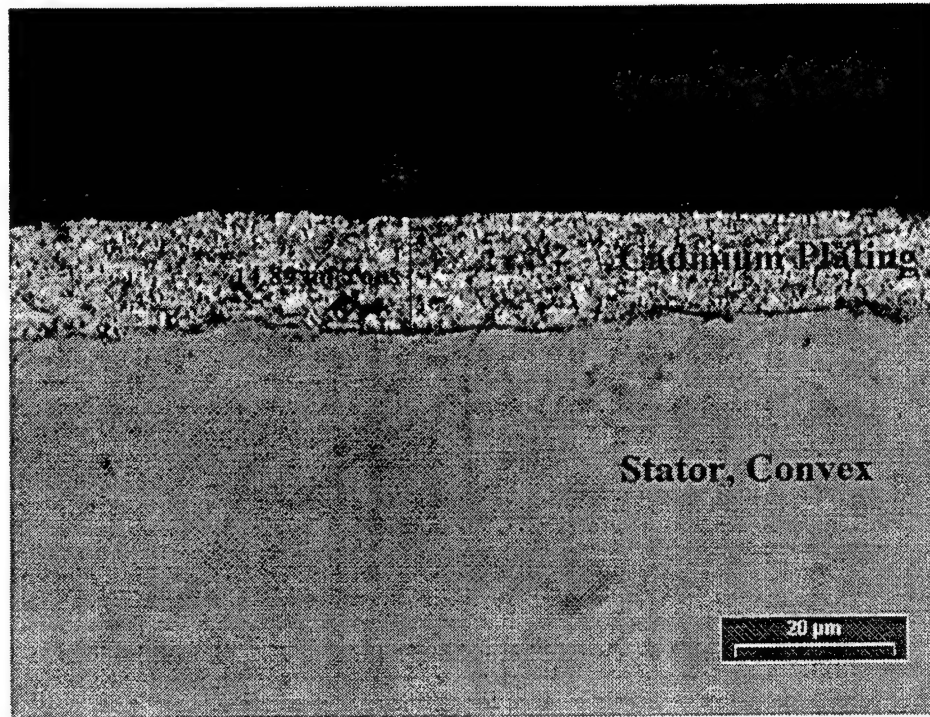


Figure 64. Cadmium Thickness, Middle of Vane, Convex Side.

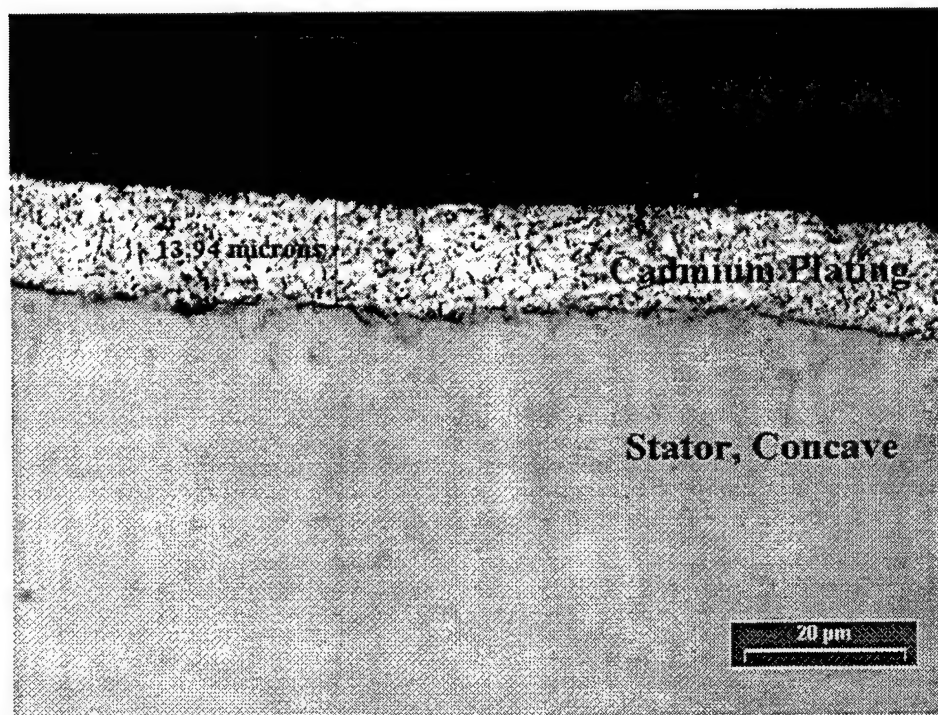


Figure 65. Cadmium Thickness, Middle of Vane, Concave Side.

Table 3. Final Stator Cadmium Plating Thickness

Component	Location	Measurement (mils)	
<u>Shrouds</u>	Outer Shroud	0.42, 0.41 ^a	
	Inner Shroud	0.29, 0.30 ^a	
<u>Vanes</u>	• Near Outer Shroud	Concave Side	0.34
		Convex Side	0.51
	• Middle of Vane	Concave Side	0.43
		Convex Side	0.54
	• Near Inner Shroud	Concave Side	0.32
		Convex Side	0.48

^a Indicates the measurement was taken more than once.

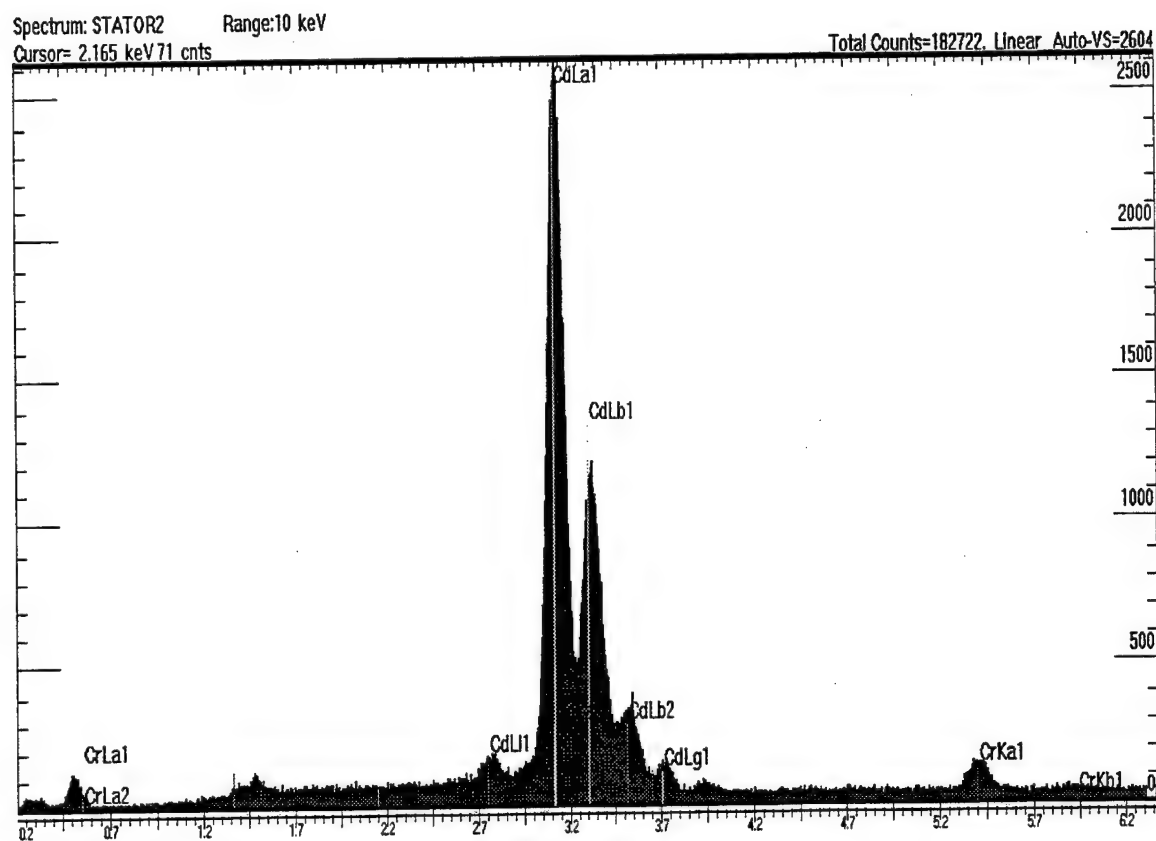


Figure 66. EDS Spectrum Indicating the Presence of Chromium.

6. Conclusions

ARL established the source of the second source vendor failure under the corrosion resistance engine test. ARL-WMRD determined that the cadmium thickness was below the required value (although the spherical ball contingency negates the requirement on over 80% of these components) and most likely was not adequately sealed. Two testing iterations were required to demonstrate this fact. The second and final iteration corrected these deficiencies and was shown to meet all specified requirements. The final stator section tested was deemed worthy of a retrial under the corrosion resistance engine test. During engine performance testing, the new corrosion resistant coating proved acceptable and the second source vendor was qualified.

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7. References

1. Avco Corporation - Lycoming Division. "Vane Assembly, Compressor - Sixth Stage." Drawing Package 2-100-060-26, Stratford, CT, 16 August 1991.
2. SAE - The Engineering Society for Advancing Mobility Land Sea Air and Space. "Cadmium Plating." Aerospace Material Specification, AMS 2400 Revision S., 400 Commonwealth Drive, Warrendale, PA, 1 August 1987.
3. American Society for Testing and Materials. "Semi-Guided Bend Test for Ductility of Metallic Materials." Standard Test Method, ASTM-E-290, 100 Barr Harbor Drive, West Conshohocken, PA, 1992.
4. American Society for Testing and Materials. "Operating Salt Spray (Fog) Apparatus." Standard Test Method, ASTM-B-117, 100 Barr Harbor Drive, West Conshohocken, PA, 1995.
5. American Society for Testing and Materials. "Measurement of Metal and Oxide Coating Thickness by Microscopical Examination of a Cross Section." Standard Test Method, ASTM-B-487, 100 Barr Harbor Drive, West Conshohocken, PA, 1990.

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13. ABSTRACT (Maximum 200 words) The U.S. Army Aviation and Missile Command (AMCOM) requested the U.S. Army Research Laboratory-Weapons and Materials Research Directorate (ARL-WMRD) investigate a corrosion problem with T-55 engine stators. This investigation was part of a second source vendor qualification in which a specific vendor was failing the engine test due to significant corrosion. The stators were virtually identical before the engine test and seemingly had passed all qualification standards. The original equipment manufacturer (OEM) of the T-55 engine stator was Avco Corporation - Lycoming Division, Stratford, CT. The second source vendor being qualified was Electro-Methods Incorporated (EMI), South Windsor, CT, and EMI's coating subcontractor Microfin Corporation, Providence, RI. ARL-WMRD performed a detailed investigation that stipulated several recommendations. Some of these recommendations were adopted, and further testing was performed. The final testing of the T-55 stators that incorporated the ARL-WMRD recommended changes provided data that indicated the engine test would be successful. Upon subsequent engine testing, acceptable results were achieved with the new corrosion-resistant coating system.				
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